AD-A146 085 REPORT OF THE WORKING GROUP ON LARGE-SCALE COMPUTING IN AERONAUTICS(U) ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT NEUILLY-SUR-SEINE (FRANCE) JUN 84 1/2

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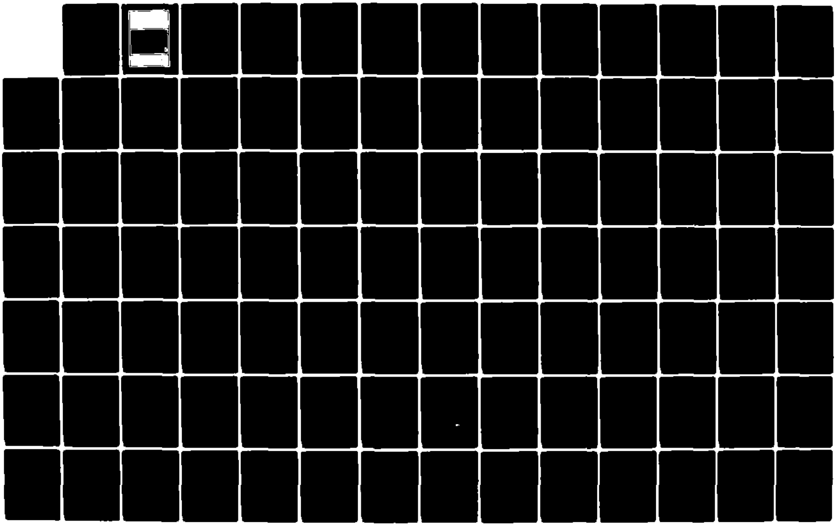

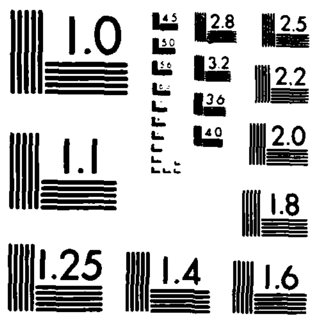

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AGARD Advisory Report No.209

Report of the Working Group on Large-Scale Computing in Aeronautics

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.209

LARGE SCALE COMPUTING IN AERONAUTICS

Report of the Working Group on Large Scale Computing in Aeronautics

This Advisory Report was prepared at the request of the Fluid Dynamics Panel of AGARD.

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– Improving the co-operation among member nations in aerospace research and development;

– Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;

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Published June 1984

ISBN 92-835-1474-2

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

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ACKNOWLEDGEMENTS

On behalf of AGARD, the Chairman of the Working Group wishes to thank all those who participated in the study, and all of the many agencies, companies and establishments which provided information, and the valuable time of their personnel, thereby making the study possible.

SUMMARY

This summary of the Working Group Report on Large-Scale Computing in Aeronautics is intended to provide the reader with the main subjects of discussion in abbreviated form and complements the conclusions and recommendations in Section 4. The summary follows the outline of the report itself, i.e., a review of the current status and future directions for computing for the primary technical disciplines in aeronautics, followed by a discussion of alternatives for large scale computing capabilities and possible organizational arrangements within the NATO community. It is recommended that the entire report be read for a better appreciation of the potential impact of large-scale computing in aeronautical research, design and development.

Fluid Dynamics

The impact of computational fluid dynamics (CFD) on airframe design has been considerable over the past few years. Current methods have demonstrated the very large economies they can bring to aerodynamic design in reducing the costs of wind-tunnel testing and in the concomitant reduction of the development time scale, leading to more efficient aircraft with consequent improvements in fuel economy, range and payload.

Traditionally panel methods, together with the boundary layer or thin-layer approach to viscous and turbulent flows, have played an important role in the description of the aerodynamics of aircraft configurations. More recently, with increasing interest in transonic performance of aircraft, a growing emphasis has been placed on the transonic small-disturbance potential approximation which captures the inherently non-linear features of the flow equations. This approach is currently being superseded by the development of efficient methods utilizing the full-potential and Euler equations to describe inviscid regions of the flow field. It seems likely that boundary layer approaches will continue to be used for flows characterized by weak interactions between viscous and inviscid regions and that zonal methods will evolve, employing the Navier-Stokes equations where necessary and appropriate approximations whenever possible, in regions of strong interactions such as wing trailing edges and separated regions.

While the major initial requirement for computing facilities will undoubtedly result from the need to analyze complete aircraft configurations in sufficient detail to predict cruise and maneuver performance, in the longer term the needs of missile aerodynamics could be as great. The accurate prediction of total aircraft drag is currently beyond the state-of-the-art and is expected to remain so until major improvements in computing capacity and speed become available. Additional uses of computational fluid dynamics, for example in wind tunnel testing and in modeling the influence of the atmospheric turbulence on unsteady aerodynamic loads for aircraft, will also be of continuing interest. It is probable, however, that satisfactory approximate methods will be used and these applications will not place more severe demands on computing capabilities. Fundamental research investigations into the details of complex fluid mechanics phenomena, including those on the origin and evolution of turbulence, will also place stringent demands on computing capabilities in the future, particularly if attempts are made to incorporate such fundamental details into the description of flows around practical aircraft and missile configurations.

Emphasis, for the next decade at least, will be placed on modeling flows of increasing complexity (attached flows with weak shocks, strong shocks, mildly separated flows, flows with large scale separations and vortices), on methods of coordinate system generation that provide high mesh resolution in regions of large flow gradients while improving overall computing efficiency, and on the creation of faster solution algorthms (explicit methods, successive line overrelaxation, rapid elliptic solvers, alternative direction implicit and multigrid methods). Pacing items that will determine the rate of progress in these directions may be summarized as follows:

Inviscid calculations - the generation of suitable coordinate systems associated with different elements of the total aircraft or missile (wing, fuselage, engine nacelle, tail surfaces, etc) the proper blending of these coordinate systems with each other, and the modeling of shock waves and vortex sheets.

Thin-layer calculations - Finite difference boundary layer calculations, improved turbulence modeling, and improved treatment of mildly separated flows, shock waves, trailing edges, wakes, wing-fuselage junctions and wing-tips.

Reynolds-Averaged Navier-Stokes solutions - the foregoing improvements in the context of strong interactions, separated flows etc., are required, together with fast numerical algorithms applied to three dimensional flows.

Large-Eddy Simulation (Navier-Stokes) - major improvements in fast algorithms are necessary even for the most simple flows before the practical application of this approach is possible.

It can be expected, at any point in the evolution of computing capabilities, that many practical applications will not be accommodated; thus for example the unsteady flow calculation for typical helicopter configurations is expected to remain beyond the state-of-the-art for the foreseeable future although the flow around important aerodynamic components such as the rotor blade may be feasible.

The computation of flows around aircraft configurations at cruise conditions will require a speed of 40 million floating point operations per second (Mflops) and a central memory of 4 million words, a capacity that can be provided by Class 6 computers. Maneuvering aircraft place greater demands on computing capabilities and lead to requirements of 10^4 Mflops in speed and 30 million words of central memory. This latter capability would also permit simple quasi-two-dimensional flows utilizing large eddy simulation techniques. These estimates do not take account of computational needs that arise from the calculation of loads and the distortions so introduced to the airframe surfaces, or of the influence of engine flows on external aerodynamics. In some cases such influences could be treated as linear perturbations to the basic flow and would not necessarily result in significant increases in required speed and memory. The foregoing demands for computer memory and speed are thought to be feasible within the next decade if past trends continue and current plans within the computer industry are fully implemented.

Structures and Materials

A review of the current status in the application of large-scale computers to Structures and Materials indicates that considerable progress has already been made. Computer programs are widely available within the aircraft industry and are used routinely in the design of major assemblies. Moreover, considerable efforts have been made in the application of computer analyses to the prediction of material properties in the failed state to utilize, more fully, cracked or buckled structures employing metallic or composite materials. With the advent of large digital computers in combination with the continuing development of finite element techniques, considerable progress has been achieved in computerized structural design in the last decade. In this section of the review substantial use has been made of responses to a questionnaire circulated to Industry, Government Establishments and Universities thoughout the AGARD community.

In static stress and strength analysis, both Finite Element and Finite Difference methods are used for a wide range of structural problem analysis. For more complex structures the Finite Element method has proved more advantageous, permitting different types of structural elements with arbitrary configuration and boundary conditions. For more simply defined configurations which can be formulated in terms of differential equations and well-defined boundary conditions the Finite Difference method is less costly, particularly when elastic/plastic effects with large displacements are involved. Present computers are sufficient to meet the needs of many practical applications; however, with the increasing use of composite materials in primary structures computer requirements are expected to increase and improved computer tools for structural analysis will be needed.

In static structural optimization, (usually weight minimization) the influence of the external shape, aerodynamic loads, structural geometry, internal loads and fuel mass must be determined in an interative fashion. Such optimization can be carried out for automated (static) structural design with conventional computers and/or array processors; the aerodynamic modules used to provide aerodynamic loads are essentially those for steady potential flow using panel methods. For the investigation of dynamic response a knowledge of the vibration parameters is necessary, and for aeroelastic stability a knowledge of the motion-induced unsteady airloads is additionally needed. When these inputs are provided finite element models and matrix methods permit dynamic response and aeroelastic behavior to be determined with essentially the same computer capacity required for static stress and strength calculations.

For modern combat aircraft in transonic flight or in the post-stall condition, new aeroelastic problems are introduced; unsteady (separated flow) airloads and transonic airloads are highly non-linear with respect to mean angle of attack and amplitude of oscillation, thereby denying the use of linear superposition and requiring the solution of the non-linear equations at each time step. Aerodynamic inputs will require computer capabilities as identified in the discussion of the Fluid Dynamics section and a combination of the aerodynamic and structural modelling using Finite Element methods is expected to effectively double the required computer capability. For the aeroelastic and dynamic response of rotary wing aircraft, the computer requirements will be substantially greater because of the gyroscopic coupling effects which introduce structural nonlinearities that add to the aerodynamic nonlinearities.

In the analysis of fracture mechanics a determination of damage tolerance of the structure in the presence of a crack is particularly important. Consequently several numerical methods have been developed to quantify the stress distribution in the vicinity of structural cracks. Numerical results, using Finite Element methods, and more recently Boundary Integral Equations, have been obtained for practical configurations. With regard to damage mechanics, methods have been developed that address the question of crack initiation prediction. Such prediction is particularly important when any crack may lead to catastrophic rupture (such as in turbine or compressor discs) and potential damage to the aircraft structure. The susceptability to the presence of macrocracks (say 1/10mm in length) leads to the allocation of a damage parameter to each volume element of the material; it is viewed as an internal state variable and characterizes the material volume element between the condition of no macrocrack and the condition when a macrocrack of critical size occurs. Two mechanisms associated with the creation of macrocracks have been identified, namely, creep and fatigue, both of which require a precise knowledge of stresses and strains throughout the structure. Crack initiation, moreover, is frequently associated with high temperature environments and subsequent non-linear material behavior. Analysis of practical problems in this field requires the use of powerful computers. In buckling or post-buckling behavior of a structure interest lies in the residual strength inasmuch as this determines, in part, the load transfer to other components. In post-buckling analysis the main ingredients are: large strains (leading to a non-linear strain tensor); several regimes from linear elastic to plastic; the use of numerical methods. Currently, due to computer limitations, analyses are restricted to simple structures although there is great interest in more complex structures such as stiffened panels with assemblies.

The user community currently uses computers of varying size up to, and occassionally including, Class 6 computers. Without exception, improvements at all levels and in all the disciplines associated with structures and materials are thought to be necessary. Improvements in capacity are necessary in order to attack many of the problems described earlier. In many applications existing computers, shared among several users, can be enhanced through peripheral equipment improvements, particularly when these involve the interactive computing role. Required improvements include more extensive and responsive terminal screens and printers, and improved graphics and color facilities. Computer networking is advocated for pre-or post-processing of mainframe data, or to link integrated design modules. Array processing is widely advocated and the need for the associated software is recognized. In both hardware and software cost considerations continue to be a strong factor in the acceptance of new capabilities.

The likely future for computing in structures and materials will include improvements over a broad front, including the increasing use of Class 6 computers, with emphasis on: improving the interactive role of mainframes; developing integrated design methods; the use of array processors; provision of adequate software; and reduced computing costs. Although the driving need for Class 6 computers and beyond will probably evolve from the needs of other disciplines, there is little doubt that they will ultimately be used extensively in structures and materials applications if they are made economically viable.

Two technical areas appear most likely to benefit from computing capabilities at and beyond the Class 6 level, namely interdisciplinary optimization and non-linear structures and materials analysis. In regard to the first of these, substantial efforts are currently being applied to computer programs capable of taking into account both static strength and dynamics aeroelastic constraints, and permiting the inclusion of transonic and separated flow unsteady airloads with active controls. Added impetus has been provided by a recognition of the advantages of composites in aeroelastic tailoring.

Currently, structural optimization involving static strength and aeroelastic constraints is being applied to individual lifting surfaces but is beyond the state-of-the-art for complete aircraft. Unsteady airloads, which can be computed by linear methods in the subsonic and supersonic regime, require non-linear equations to be solved in the transonic regime where the additional complexities arise due, for example, to moving shock waves and attendant pressure loads. Moreover the structural equations must be solved simultaneously with the flow equations leading to the need for Class 6 or greater computing capabilities.

For helicopter rotor blades the situation is further complicated by higher amplitudes of lift fluctuations, a variation of Mach number along the blade due to rotation giving strong transonic effects at the blade tip and the out-of-phase variation of local blade incidence and local Mach number. The inclusion of unsteady nonlinear aerodynamics similtaneously with structural nonlinearities arising from large amplitude deflections make the analysis and computation of the helicopter blade in three dimensions an extremely difficult problem. Again a large increase in computing capability is required to attack such design optimisation problems.

The application of active controls for flutter suppression and load alleviation is of potential benefit in aircraft design providing improved structural life and ride quality. Problems in the analysis of active control systems arise from the nonlinear dynamic behavior of servohydraulic systems, thus compounding the aerodynamics and structural non-linearities discussed earlier. Clearly supercomputers can play a significant role in this situation.

The future with regard to fracture mechanics will see substantial efforts directed toward three-dimensional geometries and states of stress, and toward non-linear behavior in the vicinity of cracks. For non-linear materials, iterative methods must be used to determine the stress distribution due to viscoplasticity, sometimes requiring a large number of iterations, and requiring a much larger number of variables compared with the elastic case. This additional complexity gives rise to a computer speed of about 400 Mflops, for a typical one hour computation, with storage requirements of 5 million words of central memory, and 200 million words of sequential access backing storage. It is expected that three-dimensional damage mechanics will become a major subject of research in the future. With the emergence of composites, directionally solidified materials, and single crystals, the problem becomes more complex due to material strain-induced anisotropy and the necessity for considering damage to be a non-scalar property. As a consequence, computing requirements for research in damage mechanisms will be similar to those given above for fracture mechanics. Post-buckling analysis in the future will include a more complete description of material behavior, e.g. plasticity models and, for non metallic materials, the anisotropy associated with the plastic behavior of the matrix. The post-buckling analysis of a structure of composite material having anisotropic non-linear properties comprising 5,000 degrees of freedom is about 200 Mflops, with storage requirements of 2-5 million words.

Thus, within the structures and materials community the following view emerges: an increasing use of current computing capabilities if they can be made widely available, more interactive and more economic, an emerging demand for Class 6 computers with appropriate software; and at present little demand for a supercomputer beyond the Class 6 level although some problems have been identified for which there may be no alternative means of solution. Clearly, the structures and materials community does not consider itself as having a driving need for a supercomputer although such a capability would undoubtedly be used if it became available.

Propulsion and Energetics

The status and needs for large-scale computing in relation to the Propulsion and Energetics community were assessed by means of a questionnaire to representatives of AGARD. Their opinions were solicited on specific items of basic research and design applications that are currently restricted by inadequate computing capability, and on the current availability and future trends in computer equipment. It was concluded that many of the requirements in propulsion were similar to those in aerodynamics and in structures and materials. However, the complex interactions between aerodynamics and structures in propulsion systems provide additional demands for computing power. In particular these demands are discussed in the areas of rocket technology; internal aerodynamics, combustion, heat transfer, and flames; and in engine-related structures.

Three aspects of rocket technology are currently inhibited by inadequate computing resources: modeling of combustion instability, including vortex shedding and turbulence; holographic diagnosis of exhaust plumes; and modeling of kinetics from the flame front to the exhaust nozzle. More advanced computing capabilities would permit the complete optimization of rocket design allowing for real time kinetics and leading to the prediciton of specific performance to within half a percent error. In regard to structural and propellent grain design, the limitation lies with an accurate determination of the physical properties and not with inadequate computing capacity.

Aircraft engine design requires that the aerodynamic performance be determined for all the components. This, in turn, requires the solution of three dimensional Navier-Stokes equations including the interactions between consecutive stages,the effects of boundary layers on the hub and shroud and their interaction with the primary flow. Due to the influence of wakes shed from the upstream stages on the flow over subsequent blades, the whole flow field must be covered by a fine mesh to fully resolve the transport phenomena to the scale of viscous diffusion. All stages must be considered simultaneously in the calculation for the transonic regime and when predicting stall and surge limits. Ultimately it is desirable to perform a complete calculation of all components (intake, compressor, combustion chamber etc. to the exhaust nozzle). Additional applications of advanced computing capabilities include the flow fields associated with thrust reversers, VSTOL jet fountains, three dimensional heat transfer calculations in blade design, and acoustic fields resulting from combustion noise.

The analysis of combustors requires (1) the modeling of turbulent three-dimensional flows with chemical reactions described by a realistic multistep reaction system, and (2) the modeling of turbulence flames involving fluctuations in temperature and gas composition and their interaction with the flow field. Large scale computers, if cost effective, would allow such modeling for combustors of realistic shape, and would permit preliminary optimization prior to fabrication of model hardware for physical testing. The use of computers in this fashion would first require a better understanding of the physical phenomena present in combustion processes, however. Problems occuring in engine structural components include vibration and flutter, in addition to materials problems such as plastic flow, buckling and those related to the analysis of non-isotropic materials (composites and directionaly solidified alloys).

Further improvements in engine design analyses are limited by inadequate computer capacity in relation to modeling of the viscous flows in three dimensions, including effects of combustion. The basic unsteady character of the flow in internal aerodynamics and the complexity of the multistage geometry lead to one or two orders of magnitude greater demand on computing capability compared with that required for the external flow around an aircraft. Computer-aided design and computer-aided manufacturing are other areas that will place increasing demands on computing power and require improvements in database capability including the input, storage and retrieval of complex geometry, engineering analyses and test results. Contemporary large computer installations are adequate for many purposes, however, and the first needs are for access throughout a research or design organization through remote terminals, and for more effective use of available hardware.

Flight Mechanics

The review of the use of large scale computing in Flight Mechanics is provided in two main subject areas, namely simulation and flight testing. It is the result of detailed and extensive questionnaire surveys, conducted with the help of FMP members, of a large number of organizations in the aerospace field representing Industry and Government Laboratories in the NATO countries. The discussion of computing in simulation includes the role of the computer in real-time manned flight simulation and the status of, and need for future advances in, computational capabilities for flight simulation and visual image generation. The discussion of the role of computers in flight testing encompasses current flight test measurement and data processing systems, and projected developments and future advances in these systems.

Considering first, large scale computing in flight simulation, it is recognized that the digital computer has substantial advantages over its anolog counterpart in terms of greater fidelity and reliability. By the late 1960s the large general purpose digital computers, embodying large input/output and high speed arithmetic capabilities, were found suitable for use in real-time simulation in most applications. Today, special purpose computers are used primarily in applications demanding very high speed processing such as rotary wing simulation and computer generated imagery. The need for real-time computation associated with the presence of a pilot in the loop, or subsystem hardware and avionics in the loop, requires that input/output time plus code processing time be less than the sample period of the computation. The computer must calculate all of the functions associated with the aircraft mathematical model with sufficient frequency to achieve dynamic fidelity for the highest natural frequency present in the solution response. For a typical transport aircraft, for example, this requirement gives rise to a computer speed of the order of 5 Mflops.

Based on the survey, the following picture emerges with regard to the current status: the application of simulators is divided approximately 70 percent military and 30 percent civil; air-combat simulators appear to be the most complex and therefore most costly; simulation use for research, design and development of aircraft outweigh their use for crew training; computational capabilities cover the entire range from minicomputers of the VAX 1170 class to the highly integrated, centralized mainframe computers of the CDC 7600 and Cyber 175 class; in some organizations hybrid systems and array processors interfaced with minicomputers are used as a means of increasing operational bandwidth as required for high frequency sampling in helicopter simulation or radar system simulation; computational speeds range from 0.2 to 10 Mflops depending on the needs of the particular organization.

With currently available computing capabilities many organizations include in their simulation fairly complex features of the aircraft including nonlinear aerodynamics, propulsion, structural motion, flight controls, navigation and weapons systems, and the simulation of the displays and the cockpit environment. Rotorcraft simulation appears to be particularly demanding on computer capability: blade flexibility, radial and asimuthal variations of blade forces and moments, nonlinear effects such as stall or transonic tip aerodynamics, rotor-fuselage flow interference and dynamic interactions all combine to defeat the ability of the largest available computers to provide real time simulation with complete fidelity. Other areas where current computers provide only limited performance include: multi-aircraft gaming environments, full-envelope control-configured vehicles with simulated avionics, and iron-bird remotely piloted vehicle simulations.

The great majority of responses to the simulation questionnaire indicated plans to upgrade the current capability through distributive networks and new generation 32 bit computers. Significant improvements in simulation will result from the development of a 32 bit microcomputer with 1 million bit memory on a single chip anticipated during the 1980's. Such devices may figure prominently in tightly coupled distributed networks uniquely configured for real time simulation, although there remain concerns regarding the associated software costs. In general it is expected that the future needs for simulation computing will be satisfied by natural computer technology developments and that general purpose computers will be preferred over special purpose devices. The simulation of rotorcraft remains as one of the major challenges, however, and it is estimated that simulation with adequate fidelity of a 5 bladed rotorcraft would require the equivalent power of 3 Cyber 175 computers, or essentially a Class 6 computer capability.

Computer Generated Imagery (CGI) is an area of rapid growth stimulated by the increasing demands for computer-based visual simulation. The survey indicates a definite trend toward CGI based on the architecture of microprocessors interfaced with minicomputors, and that further significant advances in CGI are needed for both military and civil application. General purpose computers are not expected to be economically acceptable for CGI purposes; rather the future of CGI is thought to lie with Very Large Scale Integrated Circuit (VLSIC) technology and with developments in high density optical disks to replace magnetic memories thereby providing specialized devices of very high equivalent computing power.

From the foregoing it is concluded that convincing arguments cannot be made for supercomputers developed for the support of real time simulation. The most ambitious simulation currently envisioned, the real time simulation of multi-rotorcraft gaming environments involving high performance compound helicopters, would pose severe requirements but these could be met by Class 6 machines. The needs of CGI visual systems (10^2to10^4 Mflops equivalent computing power) are more likely to be met by highly specialized developments and not through the application of large mainframe computers.

Turning now to the subject of flight testing, computerized measurement and data processing systems have in recent years become an absolute prerequisite to the successful and cost-effective accomplishment of development testing, for the qualification and evaluation of products, and for operational testing and certification. It is significant that manufacturers and flight test organizations frequently conduct several flight tests involving several aircraft simultaneously thus requiring efficient performance in a multi-aircraft testing environment. Modern data acquisition and data processing systems permit real-time and quick-look capabililty through the use of on board and ground-based measuring equipment. Due to the higher accuracy inherent in digital recording (by about 20 dB) there is a trend toward pulse code modulation (PCM) which records higher frequency bandwidth phenomena. This trend is supported by advances in miniaturization which assure acceptable weight, volume and cost. Such equipment is supplemented by airborne cameras, video cameras and recorders, the output from which can be telemetered to ground stations. Ground based measurement equipment typically includes tracking devices such as radar, laser ranger/trackers and high-speed cameras coupled with dedicated mini-computer systems. Air-combat training test ranges employ a network of tracking stations (multilateration technique) which process data in real time and transmit the data to a central processor/controller. It is anticipated that these systems will lead to fully computer-controlled time/space positioning systems. It seems probable that flight test centers which must deal simultaneously with several test programs, involving many types of aircraft and missiles in a real time environment, will see the greater need for larger computing capabilities.

A questionnaire survey on the use of computers in flight testing yielded the following picture: in the industry and the larger flight test centers current data acquisition and processing equipment is used to full capacity; many facilities use a range of computer sizes including minicomputers and the large mainframe computers (eg Cyber 74,IBM 303X etc) frequently connected by a communication network between the test center and the central computing center; rapidly changing requirements at the flight test centers motivates improvements in real-time graphics, enhaced interactive real-time computing capabilities and an expansion of computer power; software improvements are required for large bandwidth digital data processing, data management, real-time analysis, tracking and communication and for higher order computer languages, among other functions.

The continuing increases in complexity and cost of aircraft and missiles, together with the reduced time schedules for testing and evaluation, provide a major driving factor for further advances in instrumentation, communications and computerization. The whole spectrum of computers can play an important part in the modern automated flight data-handling process, with spectacular advances expected from microelectronic techniques. The development of general purpose large computers will provide enhanced batch processing capabilities but there is no special requirement in flight testing that cannot be met in the natural course anticipated for future large computer developments. However, those organizations involved in multi-aircraft testing and training in a real-time environment will benefit most from computer mainframe improvements in speed and capacity.

Integrated Aerospace Design

The use of computers in the integrated aerospace design process was reviewed by an AGARD Flight Mechanics Panel symposium entitled "The Use of Computers as a Design Tool" in September 1979. The situation at that time reflected a substantial use of large-scale computing facilities in the several contributing disciplines but also revealed the lack of a general integrated design process involving large scale computing. In the last several years, however, rapid progress toward an integrated approach appears to have been made. The current study has attempted to review the status and probable evolution of this subject primarily through the use of a questionnaire circulated to the industry.

The aerospace design process includes, in addition to the technical disciplinary areas described in earlier sections, the integration of economic, operational and environmental factors and inevitably leads to a highly interactive and iterative activity involving many people and numerous judgemental decisions. A highly automated methodology, combined with the data storage and data manipulation capabilities of the modern computer can provide a very efficient decision-aiding tool, while decision-making will remain the responsibility of the design team.

Integrated aerospace design methodology is becoming important for a number of reasons including: the increasingly complex demands placed on the design resulting from conflicting mission and performance requirements; the greater degree of interaction between disciplinary influences on the design; the need to avoid costly changes late in the design cycle; and the need for greater management visibility into design trade-offs and their implications. The computer-aided design process has the potential of meeting these needs, of contributing to improved engineering productivity, and permitting the evolution of vehicle configurations not otherwise possible. The computer hardware that will permit such design methods to be used to maximum advantage must provide large increases in speed and storage capacity, greatly enhanced interaction between computers, and between the design team and the computer complex, improved means of communication and display of information and relevant data, and the ability to interface a range of computers of varying capability as may be required by the several contributing design elements.

Software developments will also be necessary in order to integrate effectively the presently independent and frequently incompatible specialized software that has evolved in response to specific disciplinary needs over the past decade, and ultimately replace it with software that is responsive to the needs of integrated design. Such software would be characterized by: efficient storing, tracking, protection and retrieval of large data banks maintained in multiple storage devices; geometry and graphics elements permitting rapid data creation, manipulation and friendly display functions; executive control of user-directed processes and communication between distributed hardware; company-wide data bases with ready access by all appropriate engineering and management personnel. The development of software of such versatility will undoubtedly require much effort to resolve compatability problems, program language difficulties, etc., but the end result is expected to be major improvements in design and manufacturing processes.

Computer requirements for integrated design depend on whether the design is at the conceptual, preliminary or detailed level. Current computer systems are able to meet the needs at the conceptual design and in some cases at the preliminary design levels. For an integrated detailed design capability, however, much remains to be done by way of hardware and software development. A large distributed computer network system, comprising mainframe and satellite processors, interconnected through an efficient communication system can provide a short-term solution for the detailed design capability. A network of this kind would lend itself readily to future growth through the incorporation of Class 6 computers and advanced peripheral equipments as they evolve with continued technological progress.

Computer Requirements

In the preceding sections the computational capabilities required by the several disciplinary and interdisciplinary users have been discussed in terms of two simple measures, namely, speed and memory capacity. Such a simple characterization is not adequate as a statement of requirements, however, and three factors are considered here as a more complete way of expressing future capability (operational characteristics; data base and input/output activity; and computational load).

The responses to a user questionnaire circulated to a number of organizations involved in aeronautical research and development are summarized as follows:

(a) Operational Characteristics - users stressed the importance of graphic displays and other user-friendly features particularly when frequent interaction with the operator is required. Special security and proprietary data protection were recognized as necessary and, although catered for by public data networks to some degree, remain as unresolved issues in the design of any future decentralized system.

(b) Data Base and Input/Output - high rates of data transfer were identified as an important feature of most aeronautical applications; however conventional access methods were generally regarded as adequate. Heaviest demands on input/output systems arise from graphics and simulation uses and may also arise in arrangements which attempt to link local equipment to a central facility.

(c) Computational Load - to some degree, the computational load can be reduced by programming techniques and the use of special compilers; Fortran is used predominantly, with assembly language used in critical sections giving an increase in performance of 2 in scalar mode and up to 10 in vector mode. Program size did not appear as a major design factor and systems of up to 1000 subroutines comprising 30 million bits of instruction are adequate for most purposes. Addressable memory requirements varied widely with specific application, up to 10^{14} bits. Sustained rate of execution also varied considerably up to 10^4 Mflops (million floating point operations per sec). Future increases would probably demand both greater performance and more efficient algorithms. Both vector and matrix data structures appear prominently in most applications with special cases such as banded or triangular arrays occuring in fluid dynamics and structural analysis. Most computational problems are not easily compartmented into separate segments.

Existing commercially available computers include both serial processors (Cyber 170, IBM 3081, Amdahl 470 V8) and vector processors (Cyber 205, Cray 1) generally termed Class 6 computers. Computers anticipated by 1985 include more powerful Cyber, Cray and Amdahl equipment (and in addition emerging Japanese equipment), which offer up to 200 Mflops with up to 4 million word memory size. Advanced US and Japanese computers, planned for operation by early 1990's will extend this capability to 1,000 Mflops and 256 million word memory size, using newer technology and architecture.

Beyond 1990 it can be expected that advances is technology and architectural design will permit further improvements in size and speed of large central computers and, potentially, of decentralized systems. While progress toward these latter systems is somewhat speculative their potential advantages are recognized and include: modularity, giving architectural simplicity; parallel processing of independent program elements; and more efficient scalar processing. These potential advantages are offset by anticipated drawbacks, however, including hardware implementation problems (e.g. relating to synchronization), difficulty of adapting current algorithms, and user reluctance resulting from the major investment of effort required in establishing program transformation tools, new language structure etc. Currently in the research phase are architectural arrangements, such as heterogeneous element processor (HEP) systems, which use modular architecture in conjunction with a large number of the more advanced processors (eg 16x Cray 1), linked to a similar number of memory banks via crossbar switching, giving an anticipated speed of 400 Mflops. The relative advantages of this approach compared with the conventional central system approach remain to be demonstrated.

The question of the role of communication networks in aggregating computers, and thereby permitting broader access, was considered but no firm conclusions were drawn in this regard. Although such networks exist today their value is currently severely restricted by bandwidth limitations. The rate at which communications technology will remove these limitations is not easily projected and the prospects for decentralized computer systems, comprising major assets at dispersed geographical locations, remain uncertain. This issue is discussed further in the section on Large Computer Facility Options.

Large Computer Facility Options

The alternatives for providing access to large computing facilities within NATO range from a decentralized network to a centralized supercomputer system made accessible to all members. In light of the large cost of modern computer hardware and software acquisition, it is suggested than an evolutionary approach be considered; this approach would use, initially, currently available capabilities and evolve toward an improved system with improved user access by the NATO member nations. Ultimately an advanced capability, widely available within NATO, could emerge from these efforts.

Two levels of capability and need can be identified at the outset. The first level is represented by nations with major research laboratories, aerospace companies and universities involved in the use of computers in aeronautical research and development. Such organizations will have in place, during the 1980s, Class 6 computers and significant libraries of aeronautical codes for aerodynamic, structural and propulsion system design purposes. The second level of capability is represented by those nations which have very limited computer resources but which, nevertheless, are evolving in their understanding and use of modern computer techniques. Clearly the nations having a well-developed capability are in a position to assist those with emerging capabilities; indeed, in the recent past cooperative arrangements have been established within AGARD to permit such assistance by the nations having mature computational capabilities to those with substantially lesser capabilities.

Such sharing when conducted on a larger scale must of course respect the military security and competitive position of the participants. However, within these constraints, there probably remains a significant range of capabilities which lie in the open literature or which are no longer significant to the competitive position of the participant. Sharing existing capabilities of this kind through a NATO-sponsored arrangement would be an initial step in the evolutionary pattern of arrangements described earlier. Three elements are required in any sharing arrangement: a willingness to share applications codes; access to an appropriate computing machine through a terminal at the user site; and a commercial dial-up telephone service to link the user-terminals.

While the execution of such sharing schemes would be relatively inexpensive they nevertheless raise key issues which must be resolved: Will those entities with highly developed computing capabilities be willing to share them? Can those without major computing capabilities gainfully utilize them? The acceptance and implementation of even a primitive sharing plan would set precedents in permitting some external access to previously protected data and software and would establish commitments to the training of relatively inexperienced users. Such precedents may require the involvement of government and corporate representatives in order to assure that the policy issues are fully understood and the arrangements found satisfactory.

Closely related to a first level of resource sharing would be the establishment of a common laboratory installation to provide advanced training and education in the use of computer systems, and the establishment of common libraries of basic codes, algorithms etc. , which are prerequisite to creating a modern computational capability. Such an installation could be established within an existing organization thus providing an educational environment and the necessary supporting functions.

With the establishment of such a common laboratory installation the basis would exist for the evolution of a communication network with other existing computer facilities within the NATO nations. Such a network would permit the exchange of computational information and facilitate the development of new techniques in computer communications between the central system, the major resources located in the aeronautically-developed nations and the users in the nations with newly emerging capabilities. In the event such an arrangement as described above is considered attractive by the NATO nations it would be necessary to establish a governing body which would assume responsibility for establishing and operating the system in consonance with a well defined set of technical and organizational objectives. The implementation would also require the involvement of a technical organization (institution, or contractor) to create the common node and the communication interfaces to the network.

Considering further the nature of the capability established at the central node, two broad concepts have been considered briefly: The first is a large "super-center" housing and operating the most advanced equipment and shared by all members. This concept is one that is being pursued by NASA and is based on the premise that the science of applying computational methods to the aeronautical disciplines will be most rapidly advanced when the most powerful computers are placed at the disposal of a dedicated research group. It is not obvious, however, that this approach is best suited to the needs of NATO/AGARD. On the other hand, thought has been given to the idea of combining resources, located at various member installations throughout the NATO community, to form an aggregate supercomputing capability through advanced communications networking. The success of this approach depends on very high band-width communication, i.e. perhaps on a several-hundred-fold increase beyond the 50 kilobit systems currently in use. This approach is further compounded by the problems of task segmentation, resynchronization, coordination of data bases etc.

The choice between these two conceptual approaches need not be made at the present time. Undoubtedly some of the technical issues will be resolved with progress in computer and communication systems during the next several years. In the meantime the initial steps in establishing a computer center for NATO/AGARD could proceed, if found to be desirable, and its subsequent pattern of development determined by the evolving needs and the directions taken by technological progress.

1. BACKGROUND, TERMS OF REFERENCE AND WORKING ARRANGEMENTS

During the past twenty years the speed and capacity of electronic computers have increased by several orders of magnitude, effectively a tenfold increase in computing capability every five years. This growth has stimulated an increasing level of interest on the part of the aeronautical community in the application of computational methods to a variety of research and design problems. Much of this interest initially centered on theoretical aerodynamics and fluid dynamics as evidenced by continuing increases in the number of symposia and published articles in what is now called Computational Fluid Dynamics.

In the past decade, however it has become widely recognized that large-scale computing capabilities will have an important influence on a broad range of subjects related to aeronautical research and development including: structural analysis and design, materials research, the internal aerodynamics and dynamics of engine components, combustion processes in airbreathing engines and rockets, simulation of normal and emergency situations in aircraft operations, real-time analysis of flight test results, and the integrated design and optimization of aerospace vehicles.

In 1980 discussions among the Director of AGARD and the Chairmen of several AGARD Panels concluded that it was timely for AGARD to undertake a study of the subject. In March 1981 a Working Group on Large-Scale Computing in Aeronautics was established to undertake the study. Briefly the objectives of the Working Group, as reflected in its Terms of Reference were to:

1. Review the current status and likely future direction of the application of large scale computers to aeronautical R and D in the areas of fluid dynamics, structures and materials, propulsion, and flight dynamics.
2. Consider the generic types of computational facilities which would be required, and
3. Recommend any actions needed on an international basis to maximize the benefits to NATO nations of future applications of large scale computing in aeronautics.

Although this Working Group was established as an activity of the Fluid Dynamics Panel for administrative ease, it was in effect an *Interpanel Working* Group with representation from four AGARD Panels: The Fluid Dynamics Panel (FDP), the Structures and Materials Panel (SMP), the Propulsion and Energetics Panel (PEP) and the Flight Mechanics Panel (FMP). Supporting activities within each of these four panels contributed technical information, conducted surveys and provided reviews of the Final Report. A list of members and participants in the Working Group activity is given in Appendix A. The first meeting of the Working Group was held in Toulouse, France, in May 1981 and four subsequent meetings were held in London and Paris. The schedule of meetings is given in Appendix B.

It was anticipated at the outset that the status and future trends in the use of computers for the several disciplinary areas important to aeronautical research and development would be quite diverse. The results of a broad review, conducted with the aid of questionnaires and involving many organizations in Europe and the US showed this to be the case, as seen from the discussion given in Section 2. Each of the areas represented by the interests of the four Panels has unique needs for computing capabilities, some of which can be accommodated by common large-scale computer developments, others of which require dedicated and sometimes highly specialized computer developments.

Given the present status and future trends in the several user-disciplines, the evolving patterns of computer developments, both hardware and software, were reviewed and summarized with emphasis on the 1980s but with some consideration of potential developments anticipated for the 1990s. The relevant discussion is contained in Section 3 together with a discussion of possible means of providing access to large-computer capabilities by the member Nations of NATO including the Southern Flank Nations. No attempt was made to evolve recommendations regarding specific types of computer facilities that would serve all needs. Indeed, during the course of the study it became clear that a variety of computing facilities may be required in the future and that member nations could be expected to pursue individual plans and strategies in acquiring them.

However, much attention was given during the study to the possible sharing of computer resources among member Nations, and to the question of how best to provide large-computer access to essentially all member Nations for the purpose of training, code development and upgrading of local capabilities through computer networking. The discussion of these issues is also given in Section 3.

It is clear that the computational needs in aeronautics will continue to develop during the

1980s and 1990s and that they will be accompanied by significant developments in computing capability. The conclusions of the Working Group in this regard are to be found in Section 4. Although the study has not resolved certain important questions relating to the sharing of computing resources among member nations, it has nevertheless recommended a way to facilitate greater access by member nations through the establishment of a NATO Computer Center for Aeronautics. The recommendations are to be found in Section 4.

Finally, in light of the growing interdisciplinary nature of aeronautical research and development it appears likely that new mechanisms must be used to assure the adequate integration of technical efforts within AGARD. In this regard, it may be said that the Working Group on Large-Scale Computing in Aeronautics has been a successful exercise in interpanel cooperation and coordination, calling on the technical strengths of four Panels and combining their diverse inputs into a single report.

2. CURRENT STATUS, FUTURE NEEDS AND DIRECTIONS

The current use of computers in the aeronautical disciplines and applications, and the character of the future needs and directions, vary widely due in part to historical differences and in part to different perceptions regarding the value of computational approaches. Specific needs, moreover, depend uniquely on the task to be undertaken, as for example in real-time flight simulation or in image processing and display.

For these reasons, this Section is organized into 5 parts corresponding to Fluid Dynamics, Structures and Materials, Propulsion and Energetics, Flight Mechanics, and Integrated Aerospace Design. Each part of the section is self-contained and includes References or Bibliography, Appendices as necessary, and a list of contributing organizations and individuals. Each of these parts is associated primarily with a particular AGARD Panel, moreover, and each reflects the views of the appropriate contributing Panel. Additionally the entire Section was discussed at length by the Working Group and reflects its combined views of the subject.

2.1 Fluid Dynamics

2.1.1 Introduction

The advent of the large digital computer has opened the way to the application of theoretical methods to aircraft design to an extent which was almost inconceivable 20 years ago, though their application to missile design is lagging. At that time linear theories for the inviscid flow together with semi-empirical predictions of boundary layers were the theoretical tools used as a guide to the wind-tunnel tests on which design essentially depended. What has been described as a revolution[1] started about ten years ago when the first numerical solutions for mixed flows (that is, flows with both subsonic and supersonic regions) about aerofoils appeared[2,3] following the previous demonstration by Sells[4] of the power of numerical methods in calculating subsonic flow. The revolution is however far from complete and its progress is dependent primarily on four factors: the power and storage capacity of the computers available, the ability to generate coordinate systems for complex configurations, the construction of algorithms for the solution of the flow field equations which can deal with discontinuities arising from shock waves and vortex sheets and lastly, but by no means least, the capability for modeling turbulent flows. It goes without saying that the last three of these will not be achieved without the availability of teams of workers of high quality. The primary purpose of this paper is to point up the requirements for computers by assessing the current status of computational fluid mechanics and the benefits to aeronautical design so far conferred, and to speculate as to future developments. The terms of reference cover external aerodynamics, basic fluid mechanics including acoustic phenomena and atmospheric turbulence, and wind tunnel testing. On present prognostications it is clear that it is the calculation of the flow around an aircraft or missile configuration, together with the required turbulence modeling, which is the dominating item but some reference is also made to other aspects.

2.1.2 The Use of Computers in Fluid Dynamics

(a) Airframe Aerodynamics

It is in fact a difficult time to assess the current status because recent developments in methods for solving the Euler equations[5,6] have disrupted what had tended to be the accepted development course of calculations for inviscid flow, that is, the sequence from the small-perturbation equations through the full-potential equations to the Euler equations. Nevertheless, the capabilities of the methods and the advantages of their use can be demonstrated by illuminating their performance at the lowest level of sophistication of field methods while noting the shortcomings which require future advances. Linear panel methods are not considered because they are unlikely to be dominant with respect to computing requirements, although it is acknowledged that the methods will continue to play a role for some time to come in aircraft aerodynamics, because of their versatility with respect to complex geometries.

An extensive review of the development and outlook for computational aerodynamics up to 1979 was given by Chapman[7] in his Dryden lecture. He demonstrated clearly the capabilities of the various stages of numerical methods, and his paper is an essential reference in any consideration of the status and future of the subject. However, in the context of the present study it is felt that a few examples of the application of numerical methods to aircraft design problems are appropriate.

The first example concerns the design of a fixed wing combat aircraft taken from Holt and

Probert[8]. The paper discusses the design of a wing which is sufficiently thin to give acceptable supersonic performance while meeting three primary design points, namely: sustained manoeuvre, M = 0.9; sea level dash, M = 0.9; sustained manoeuvre, M = 0.8, and other secondary design points.

For a wing of given shape the first two design points are incompatible in that a good design for high lift will lead to a wing with large suctions on the lower surface and hence a low drag-rise Mach number. Thus the design of a wing with leading and trailing edge flaps was considered. In addition the difference in loadings on the wing implied a large change in aeroelastic distortion between the sustained manoeuvre and sea-level dash conditions. To design such a wing by a purely empirical approach in a wind tunnel would be a formidable task requiring many models. The transonic nature of the flow excluded the use of sub-critical theoretical methods and hence the only rational approach was the use of a transonic flow calculation method and in fact a transonic small-perturbation method (TSP) was used. The planform chosen was of aspect ratio 3.3, with leading-edge sweepback 42° and taper ratio 0.3. The leading-edge flap had a chord varying from root to tip of 5% to 12% and the trailing-edge flap had a chord of 20%. In both cases the flaps were faired to the main wing by flexible skins extending over a chordwise distance of 8% of local chord. The calculated pressure distributions which included allowance for aeroelastic twist are shown in Figure 1 and compared in Figure 1a with measured distributions. There are shortcomings in this comparison, not unexpectedly, because of the omission in the calculation of a sufficiently accurate representation of the body and of viscous effects, and also due to the limitations of the TSP approximation. Nevertheless a successful design has been achieved needing only one tunnel test to confirm rather than many, the economy being due entirely to the use of a flowfield calculation method.

The second example demonstrates the capability of a non-linear field method (again TSP) in dealing with flows over complex shapes. Boppe and Aidala[9] use a system of nested grids in which independent grids are constructed for individual components so that the mesh density can be high in regions where flow gradients are expected to be high. Because the TSP equation with its planar boundary condition is used, single rectangular coordinate arrays can be used for many components. Examples of applications of the method include[9] a combat aircraft with foreplane, a wing-fuselage combination with nacelles and the very complex configuration of the Space Shuttle in its launch configuration, all at transonic conditions. Of these only the first is reproduced here.

Figure 2 shows comparisons of predictions of pressure coefficient compared with experimental measurements for a combat aircraft configuration which has a highly swept wing and foreplane. The comparison demonstrates both the capabilities and the shortcomings of the calculation method. The capabilities are that the method deals with a complex configuration at transonic speed and high incidence and shows the main features of the interaction of the foreplane on the wing. The obvious inadequacy is the failure to deal with viscous effects which lead to separations on the foreplane and over the outboard region of the wing, where there are apparently separations on both surfaces, presumably as a result of a combination of upwash from the foreplane and an excessive leading-edge droop. There must also be some question on the ability to model the foreplane-wing interaction because of the fixed wake trajectory inherent in the basic calculation method. The outcome of this example is thus to show a remarkable capability in dealing with a complex geometry by means of relatively simple modeling using a rapid program (of the order of 10 minutes on a CDC 7600) and to indicate the need for improved modeling- viscous effects, separations and boundary conditions.

These examples made use of small perturbation methods. Such methods are currently the most advanced in dealing with complex geometries and in dealing with viscous effects (see eg Lock[10]), but methods based on the solution of the full-potential equations are also in practical use. The capability of these methods from the aircraft designers' point of view was recently discussed at the meeting at NASA Ames "Transonic Perspective, A Critique of Transonic Flow Research." Two papers from this meeting putting the view of the designer of combat aircraft and transport aircraft respectively are those of Bradley[11] and Henne[12]. In both these papers the potential economic benefits in design of using computational methods are stressed. In Henne's paper a comparison is made of the cost of developing a modification to a wing design to eliminate an exessive suction near the leading edge over part of the span, empirically in a wind tunnel and by using a computational method. For the former the time taken is quoted as 2 years and the cost $600k, for the latter the time is 1 week and the cost $10k. In Bradley's paper, the need for methods which can calculate separated flows at transonic conditions is emphasised by noting that in developing the strake on the F-16 over $4M was expended in engineering and testing 109 configurations.

As a meaningful example of current capabilities of the finite element method we can choose the paper of Heckmann[13]. It concerns the interactions between components of a configuration (wing-body-nacelle-pylon) taken from the FALCON-20 at Mach 0.79. The replacement of originally mounted engines by new ones with higher power and larger size had led to an increase in the drag. Suspecting an enlargement of supersonic regions with shocks and separations, the designer made a series of wind tunnel and flight tests. Later, a finite element code became available for solving the FP transonic flow equations around this complex configuration, and some comparisons were done allowing the validation of this finite element method. Despite the relative coarseness of the spatial discretization, a good agreement between calculations and experimental measurements was reached. In figure 3 three figures are reproduced from reference 13 showing the finite element grid used.

The above examples are concerned with the broad design objectives, but the methods also have important roles in subsidiary design or as diagnostic tools. An example of the former is the determination, from a knowledge of the stream-lines of the flow round a wing, of suitable locations for stores; of the latter the identification of the cause of some feature in stability characteristics, from a knowledge of the onset flowfield from one component on another. These roles can be exercised even when the calculation methods are not capable of treating a complete configuration.

An attempt to summarize the present status of methods for computing steady flows is given below with the type of flow to be calculated used as the main classification. In this summary 'inviscid flow' has the obvious definition, 'weak viscous interaction' refers to flows in which the boundary layer is attached, and 'strong viscous interaction' refers to flows in which the viscous effects have a dominating influence, such as at trailing edges, for shock-wave boundary-layer interaction and for separated flows. This summary is followed by a review of the current status of unsteady flow computation.

(i) Inviscid Flow

Linear panel methods are well established for subcritical flow on complex configurations, and there has recently[14,15] been some effort aimed at extending panel methods into the non-linear (transonic) flow regime. Methods for transonic flow based on the small-perturbation equations are in use for fairly complex configurations including tandem lifting surfaces and stores and engine installations. Methods based on the solution of the full-potential equations are in use for wing-fuselage configurations and are being developed for more complex configurations. Methods based on the solution of the Euler equations must ultimately replace the foregoing in order to deal confidently with shock waves in transonic flow and also to deal with mixed supersonic flow. A barrier to their development has been the large computer cost if shock waves are to be defined clearly. Recent developments promise economies and methods have been applied to wing-fuselage configurations but with a coarse grid.

(ii) Weak Viscous Interaction

Methods are well-developed for flows over aerofoils in which boundary-layer effects are taken into account, and are in current use in design applications. The methods developed furthest use separate calculations for the inviscid and viscous flows with a matching process, the inviscid flow being calculated by the full-potential equations. Some questions remain about the treatment of shock waves and of the trailing edge. Additional problems for multi-element aerofoils such as wake boundary-layer interaction require further research. For finite wings methods are developed less completely. In addition to the same problem noted for two dimensions advances are needed in dealing with wakes, wing-fuselage junctions and wing tips. Nevertheless matching methods are in use and have proved their worth in design applications.

(iii) Strong Viscous Interaction

This is a field of great research activity but as far as the authors are aware there are no 'standard' methods in routine use. For two dimensions special solutions have been obtained for trailing-edge flows, and for shock-wave boundary layer interaction in matching calculations, and 'inverse' solutions are under development for separated flows. So-called Navier-Stokes solutions have been obtained for separated flows over aerofoils including shock-wave boundary-layer interaction and, particularly for unsteady flows, have succeeded in modelling quantitatively features previously understood only qualitatively from experiment. For vortex-type separations as from slender wings or slender bodies calculations have been made using inviscid flow models in which the vortex sheets originate from specified separation lines. Only for laminar flow have fully interactive calculations been made. Little progress has been made on the modeling of general three-dimensional separations.

(iv) Unsteady Flows

Unsteady aerodynamic calculations performed as part of dynamic aeroelasticity studies in the transonic regime can be expected to require special computing requirements for two main reasons. The first is that the nonlinear flow equations will need to be solved both time-accurately and in three dimensions. The smallest aircraft component that can be considered realistically for advanced flutter calculations is a complete wing; in the case of military aircraft, interfering surfaces, wing-body combinations, external stores, etc. are likely to have to be included as well. Secondly, the most critical flutter conditions are likely to occur in Mach number regimes where superposition of the aerodynamic solutions is questionable. In this case, the structural equations should be solved simultaneously with the flow equations. Finite element modelling of the structure would typically require additional computer memory comparable to that of a three-dimensional, unsteady small-disturbance aerodynamic code, and the coupled calculations typically have to be run through twice as many cycles of oscillation as a purely aerodynamic case in order to determine whether flutter will develop. Therefore, nonlinear flutter analysis can be expected to approximately double both the computer memory and speed requirements compared to solving the flow equations alone.

Borland and Rizzetta[16] describe a preliminary effort along the lines described above. They solved the inviscid small-disturbance flow equations, made simplifying assumptions concerning the structural modes, and restricted themselves to simple wing planforms and a $60 \times 20 \times 40$ computational grid. Within these limitations, they used 160,000 words of small core memory plus about 1 million words of extended core on a CDC 7600 computer. The calculations required about 4 seconds CPU time per time step, or about one hour per case. Work is in progress to adapt the code to a *Class 6 computer, which is essential if the aforementioned limitations are to* be relaxed. Thus it is felt that coupled aerodynamic and structural dynamic analysis for advanced aircraft operating in the transonic regime will require large-scale computing facilities.

(b) Helicopter Rotor Aerodynamics

The helicopter industry has been less aggressive in pursuing the potential benefits of large computers than the fixed-wing aircraft community, even though the aerodynamic and structural dynamic phenomena are more complex for rotorcraft. At least in the USA, projects for near-term improvements to large rotor airloads prediction programs are being designed to utilize current systems such as *VAX 11/780, IBM 3033, and in some cases, CDC 7600. Therefore, the* aerodynamic modules in these programs are necessarily rather simple.

However, the various simplifications of the complex vortex wake and its induced velocity field are often unsatisfactory in hover and at low forward flight speeds, and the empirical fine-tuning used by industry cannot be used with confidence. Current extensions, the so-called free-wake analysis, typically require storage for several arrays on the order of 100,000 words each. In addition, for many flight conditions, finite-difference transonic calculations should replace the subsonic or incompressible approximations that are presently made in the lifting line or lifting surface representations of rotor blades. Finally, viscous effects in the forms of retreating-blade dynamic stall and advancing-blade shock wave-boundary layer interaction should be included. The inevitable combination of more exact mathematical models of the blade-tip vortices and rotor wake structure, viscous-inviscid interaction, and three-dimensional unsteady transonic codes for the blade tip regions can be expected to increase the computational requirements into the Class 6 regime.

Considering only the purely aerodynamic phenomena, the computer speed and memory requirements for the three-dimensional, unsteady transonic computations, with or without viscous-interaction effects, seem to be comparable to those for fixed wings, whether small-disturbance, full potential, or Euler approximations are used for the inviscid flow. The requirements for new free-wake models are difficult to estimate. In near-term research, tip-vortex rollup and viscous core effects will be studied, but after these efforts progress beyond the research mode, they can probably be kept more or less within the bounds set by the large Euler codes. Retreating blade stall will probably continue to be treated with semi-empirical methods that pose only modest additional computational power. Complex blade-vortex interactions could conceivably require Reynolds-averaged Navier-Stokes treatment, but this would most likely be confined to local regions that would be patched into larger inviscid fields. Aerodynamic interference between various rotorcraft components is likely to require somewhat more computational effort than fixed-wing cases, but this is also basically an inviscid problem.

The aforementioned facets of helicopter aerodynamics appear to translate very roughly into memory and speeds of 5 to 10 million words and 10 to 20 Mflops, respectively. Anticipating the results of the discussion in Section 2.1.4 of this report, the conclusion, then, is that even though helicopter aerodynamics will probably not be a major driving factor in the development of large-scale computing facilities, it potentially poses an additional area where such facilities could be used to advantage for aerodynamic calculations.

(c) Missile Aerodynamics

While the use of computational fluid mechanics in aircraft aerodynamics is quite extensive, its use in missile aerodynamics is lagging. The position was reviewed recently in a paper given by Klopfer and Nielsen[17] at the Fluid Dynamics Panel symposium on Missile Aerodynamics held in Norway, September 1982.

The main reason for the limited use so far of computational methods in missile aerodynamics is that the flight regimes for aircraft and missiles can differ so much. For example, with transport aircraft accurate aerodynamic data are required over a limited range of conditions (eg cruise), whereas for missiles, aerodynamic data are required over a wide range of incidence, roll angle and Mach number. A summary of the differences between the aerodynamics of transport aircraft and missiles is illustrated in figure 4. Transport aircraft typically consist of high aspect ratio monoplanes flying at small angles of incidence in the low-transonic speed range so that the flow field is essentially irrotational except in the boundary layer region. On the other hand, missiles typically consist of low-aspect ratio cruciform wings and tails and fly over a wide range of incidence and Mach number, with the result that large-scale flow separations can be expected and rotational effects are important not only in the boundary layers, but throughout most of the flow field as well. However, there is likely to be more common ground between missiles and combat aircraft at high angles of attack.

The wider operating envelope of missiles means that the transonic small-perturbation equations and the full-potential equations currently used in aircraft applications are of limited use in missile applications, being only of value in cases where the shock waves are weak and where the flow can be considered to be effectively irrotational, ie only for very small angles of incidence. Thus until numerical methods for solving approximations to the complete Navier-Stokes equation are more highly developed, together with the availability of increased computer size and power, the application of computational methods to missile aerodynamics will continue to lag behind transport aircraft aerodynamics.

Of the flow equations reviewed in Section 2.1.3, the Euler equations are the simplest subset of the Navier-Stokes equations that will account for highly rotational flows with strong shock waves and specified separated flow regions, and may be considered as the inviscid limit of the Navier-Stokes equations. However, for missile aerodynamics the proper resolution of vortex sheets is equally as important as the resolution of the shock waves, if not more so, with the result that the use of Reynolds-Averaged Navier-Stokes equations will be needed for tackling the more complex flows.

Thus the emphasis of methods for missiles is likely to be different from that for aircraft applications. Missile aerodynamics needs to address the complex flow fields around fairly simple shapes (in co-ordinate system terms) with moderate ultimate accuracy being acceptable, but high reliability being essential. This contrasts with aircraft aerodynamics where more complex and detailed geometries have to be tackled, but over a more modest range of flow conditions, with a probable requirement for greater ultimate precision. Thus the requirements of missile aerodynamics with regard to computing power are likely to be as equally demanding as those for aircraft applications.

(d) Wind Tunnels

The role of computers in wind tunnel testing is being discussed by two AGARD Fluid Dynamics Panel Conveners Groups[18,19]. The first of these groups[18] investigated the integration of computers and wind tunnel testing. They considered two items which are within the context of this report: the use of computational fluid dynamics (CFD) to correct and extend wind tunnel data, and the possibility of achieving more efficient use of tunnel time through interactive use of real time computation. The first of these should not place great demands on computer speed; however the conclusion of the group was that the priority for such work is not great enough to drive the requirement for developing this capability, rather that the use of CFD in such a context will grow naturally as skill in computational techniques and power of available computers grows. The second conveners group[19] considered, among other items, the use of the adaptive wall concept in wind tunnel testing. So far the technique has required on-line computation of the flow-field far from the model, so that relatively unsophisticated CFD methods have sufficed. As this subject expands the rate at which changes can be made in the wall shape will become important and may be limited by computer speed. Again this requirement is likely to follow, rather than drive, the advances in computation and computer power.

(e) Acoustics

The most comprehensive program currently available for the prediction of aircraft noise is probably the NASA Aircraft Noise Prediction Program [20] (ANOPP). The program incorporates prediction of the source noise, the effects of aircraft attitude, location and motion and the effects of atmospheric and ground-impedance characteristics. At its most advanced level it is capable of identifying discrete tones as well as broad-band noise defined in $\frac{1}{3}$ - octave spectra. No details of computer requirements are given but to quote from ref. 21, "A typical CTOL noise prediction including trajectory analysis, atmospheric modelling, propagation and ground effects, and calculation of component and total noise levels at selected observer positions, can all be accomplished in one computer run with turnaround time on the order of an hour or two", and thus existing computers are adequate to deal with the current application.

A difficulty in estimating future computing needs in aero-acoustics stems from two effects that tend to work in opposite directions. On the one hand the acoustic pressure is not needed to anything like the same accuracy (in absolute terms) as the aerodynamic pressure because of the conversion to decibels, but on the other hand the calculated acoustic field is a small byproduct of the unsteady flow and is very sensitive to the aerodynamic assumptions made. This sensitivity means that in order to calculate the acoustic sources generated by turbulent flow it is necessary to specify the flow field with considerable precision. A general knowledge of acoustic sources can be obtained from a Reynolds Averaged (see Section 2.1.3) Navier-Stokes computation, as has been done in the past, but for a specific calculation of a particular flow a Large Eddy Simulation (LES) would be a minimum requirement since it is not certain that the main noise sources are associated with the large eddies. It is usually assumed that the turbulent flow can be calculated independently of the acoustic field on the grounds that the latter will have a negligible effect on the turbulence. This is probably true for fixed-wing aircraft (although it has been shown[22] that acoustic radiation can destabilise a single eddy) but for a rotor blade with transonic tip regions it may be desirable to calculate both fields simultaneously.

Another difficulty in predicting aircraft noise is that in the early part of its path to the ground at least some of the noise will have to propagate through the aircraft's own shear flow. Since at that stage the noise is at its most powerful, the ordinary equations of linear acoustics may not be good enough, and it may be necessary to use more exact non-linear equations. This would require a field calculation similar to that for unsteady aerodynamics and since the noise spectrum usually covers a wide range of frequencies a fine mesh would be needed over that region of space where non linear effects remain significant.

(f) Atmospheric Turbulence

If it were supposed that the need to determine the influence of the atmosphere on the aerodynamic and structural response of an aircraft depended upon detailed theoretical modelling of the characteristics of the atmosphere then the computer requirements could be enormous indeed. The solution of the Navier-Stokes equations for the flow about an aircraft in a uniform stream would be a trivial task compared with determining the details of the earth's atmosphere with its additional complications of heat sources, gravitational and rotational effects, water vapour, surface features and so on. Fortunately this is not a realistic aim. To quote from Etkin[23] "The goal of aeronautical engineers is to design and operate airplanes safely. To this end we need engineering models of the wind that are satisfactory for design and analysis, we need to know what conditions are dangerous for flight, and we need warning systems to enable us to avoid these dangerous conditions. It is a great help that for many applications the engineering models need to describe only the "worst case" - the largest gust, the most intense turbulence, the worst shear that is encountered with some specified low probability. When structural fatigue is the issue, the "worst-case" philosophy is not so simply applied. The rate of accumulation of fatigue damage depends of course on the particular missions or routes on which an airplane is used. But these are not in general predictable in advance of production. To design for the worst possible operational life history may unduly penalize a whole fleet, since where fatigue is concerned, inspection intervals can be adjusted to allow for different operating conditions. Physical reality matters because the models we use will be truly successful only if they are intelligently related to it. Otherwise, new departures in design will be risky. Nevertheless engineering models do not have to reflect all of the true variability of the wind".

Thus the requirements for determining atmospheric characteristics can be met by relatively simple models of gusts or turbulence or shear which, while being derived largely on an empirical basis, are compatible with the known physics of turbulence and which have been developed over the 70 years of aviation to provide safe and economical design. Etkin goes on to remark that the most significant modern development "has been the advent of truly massive computing power which makes it possible to use sophisticated wind models in conjunction with elaborate airplane models." The most elaborate published method in this context is the joint NASA-Boeing DYLOFLEX computer program[24] for calculating dynamic loads on flexible aircraft including the effects of active controls. The program incorporates up to 70 structural modes, the input disturbance can either be a discrete gust or continuous disturbance, the aircraft aerodynamics are modelled by a doublet lattice method and the equations of motion are linearized. The program is written to execute on a CDC-6600 series computer, and so in its present form does not put heavy demands upon computing facilities. However, with respect to its aerodynamic formulation, if it were required to model flows with strong shock waves the linear doublet lattice method incorporated would be likely to prove inadequate and the more advanced methods of Section (a) would be required. In the very long term the combination of these methods with the other components of a program serving the function of DYLOFLEX could require computer powers in excess of those for the purely aerodynamic requirements. This report does not, however, address this problem here.

It is perhaps worth pointing out that a computer capable of large eddy simulation would in principle be able to predict local weather conditions in the immediate vicinity of an airport. This would depend on having appropriate ground measurements so as to supply the initial data. Moreover, in order to predict local conditions on the basis of current measurements, the computer would have to be able to carry out LES rapidly enough to update the picture almost continuously. The requirements would therefore be similar to those for an advanced stage of LES; on the other hand the benefits could be very considerable. This topic is briefly discussed in reference 25.

2.1.3. Prospects for Computing Aerodynamic Flows

It is concluded from the brief survey of Section 2.1.2 that, in the aeronautical field covered by this study, the major requirement on computing facilities will stem from the application to aircraft, helicopter and missile aerodynamics and the attendant needs to model the associated complex fluid mechanics phenomena. Attention is therefore concentrated on these aspects in forecasting future requirements.

Before attempting to determine particular types of calculation which will define required computer size and power, various general aspects will be considered. These aspects are the equations to be solved (i.e the successive approximations to the full Navier-Stokes (N-S) equations), the flow complexity, coordinate system generation and solution algorithms. The ultimate aim of solving accurately and swiftly the full N-S equations (without recourse to turbulence modeling) for flow around a complete aircraft configuration (such as a combat aircraft manoeuvring at transonic speeds) is unlikely to be achieved this century, if ever. The more modest exercise will therefore be pursued of assessing the levels of approximation that are tolerable for various types of flow, and identifying which of these can reasonably be expected to be amenable to practical attack during, say, the next 10 years.

(a) Flow Equations

It is assumed that linear and small-perturbation methods will receive relatively little attention in the future so that the choice of flow equations will be between the viscous Navier-Stokes (N-S) equations, with various levels of turbulence modelling, and the inviscid equations (Full Potential (FP) or Euler) with viscous effects in thin shear layers calculated separately and matched to the inviscid flow. This latter approach is attractive for several reasons:

(i) The equations solved (both the inviscid and the thin shear layer equations) are simpler than the N-S equations;

(ii) More of the problems can be attacked in parallel, for example one set of workers can work on the inviscid equations, a second set on the thin shear layer equations and a third set on interactively marrying the two methods;

(iii) The methods are currently well advanced. FP solutions about complete aircraft should be available within the next three or four years, with Euler codes perhaps one or two years behind. Boundary layer codes for attached flows over wings are in current use and more complex flows will no doubt soon be accessible to calculation; and

(iv) Required computer speed is at least an order of magnitude less for this approach than for N-S. This is partly because of the simpler equations solved, which in turn permit simpler solution algorithms, partly because of the economy in the number of grid points and partly because of the faster solution algorithms available. Until recently it was thought that solutions of the FP equations could be obtained in a much shorter time than those of the Euler equations. However, it seems that the gap is narrowing and that Euler codes[5,6,26] may soon take over from FP codes as the main methods of solution for the equations of the inviscid flow. They have the great advantage of being able to model vortex sheets and shock waves accurately (at any rate in principle), whereas, because of the assumptions of irrotationality and isentropy, FP codes do not.

Despite the advantages of this approach it must be expected that N-S codes will play an increasing role, both because of the greater complexity of the flows which they can treat and because of the greater confidence that can be be placed in their solutions (a similar example is the movement away from TSP towards FP, despite the relative simplicity and versatility of the former). The main problem with the N-S equations is how to model turbulence (in a more general way than is necessary in the thin shear-layer equations). Methods of modeling can be split into two broad categories, termed by Chapman[7] Reynolds Averaged (ReA), in which all turbulent eddies are modelled, and Large Eddy Simulation (LES), in which large eddies are computed and sub-grid scale ones are modeled. LES methods are in their infancy and require at least 2 orders of magnitude more computer power that ReA methods. It seems likely that, during the next 10 years, LES codes will be developed only for simple flows but, nevertheless they should provide much useful information which can assist in the formulation of turbulence models for the ReA codes. Spectral or pseudo spectral methods have been developed since 1971 for homogeneous turbulent flow calculation. Two kinds of codes have been implemented, the first one[27,28] is concerned with direct computation of all turbulent eddies and can only be used for very small Reynolds number, and the second[29] uses a filtering technique and a modeling of the sub-grid scales.

(b) Flow Complexity

Various situations which need to be computed or modeled will be described roughly in ascending order of complexity. In doing so it is assumed implicitly that methods of practical value will need to be able to deal with real flows, which include viscous effects, so that the problems of treating inviscid flow should not be considered in isolation, but as part of the treatment of the flows categorized as weak or strong viscous interaction in Section 2.1.2. The simplest flow equations which should provide a satisfactory simulation at each level will be indicated.

(i) Attached flow with no, or weak, shock waves. This can often be an adequate assumption for the situation at cruise for both civil and military aircraft and is a very important design point. FP codes with viscous boundary layer and wake interaction should be adequate. The extension to the modelling of vortex sheets and mildly separated flow ((iii) and (iv) below) would obviously improve the capability of the calculations and increase their range of applicability.

(ii) Attached flow with strong shock waves. Euler plus viscous boundary layer and wake are needed with special attention to the regions of strong viscous-inviscid interaction.

(iii) Vortex sheets, for example from strakes or wing tips. Models of these should be capable of inclusion in (i) or (ii) above within a few years.

(iv) Mildly separated flows. Provided the thickness of the separated region is of a similar order to that of the boundary layer this type of flow should be treatable within boundary layer theory.

(v) Large-scale separation. To treat the types of flow encountered by manoeuvreing military aircraft or missiles, including such unsteady phenomena as buffet, the N-S equations are likely to be needed but some progress can be made by simpler modelling e.g. vortex sheets from slender configurations may be treated as being inviscid as noted above. It is expected that the ReA form should provide a realistic enough simulation, perhaps with some support in the development of turbulence models from LES codes when these become available as well as from experiment.

(c) Coordinate System Generation

Before embarking on a numerical solution to the flow equations for flow about an aircraft or missile configuration it is necessary to transform the infinite physical space outside the configuration into a finite computing space in such a way that coordinate surfaces are closely packed in regions of high flow gradient, such as close to the vehicle surface. The usual way of achieving this is to develop a surface-fitted coordinate system; not only does this make it easy to pack coordinate surfaces close to the vehicle surface, but it also simplifies the task of satisfying the surface boundary conditions (eg zero normal and, for viscous flow, tangential velocity). For the N-S approach a surface-fitted coordinate system is probably a necessity, because of the need to pack closely coordinate surfaces in the surface normal direction, but for inviscid calculations a non-aligned grid system may, at least in the short term, enable flows about complete configurations to be calculated more simply (for example, the coordinate systems used in TSP calculations could be used). The separate boundary layer calculation will, of course, need to utilize a local surface-fitted coordinate system, but this need not match closely the global coordinate system provided adequate interpolation procedures are available.

Except for fairly simple configurations it seems unlikely that a satisfactory method will be found of producing a single surface-fitted coordinate system (i.e. the configuration is to be transformed into a sphere) allowing the flexibility to pack coordinate sufaces where desired. The more promising approach, such as that described by Lee[30], would seem to be that of dividing up the complete computing region into several blocks and applying a different surface-fitted transformation within each block (for example a fuselage or nacelle may require a locally cylindrical polar coordinate system). The solutions may have to be matched or patched along common block boundaries, or alternatively, as in Lee's approach, the computational domain may have a highly irregular shape. This technique is thought to be the one which will be most widely used for complex configurations in the future.

(d) Solution Algorithms

The most widely used class of solution method is the finite difference approach, but finite element and spectral methods will be described later in this section. The finite volume approach has some of the features of a finite element method in that it is supposed to be fairly simple to apply in an irregular solution domain, but the solution algorithms used are similar to those used for finite differences, rather than the variational principal invoked for finite elements.

(i) Finite difference methods

The trend over the last 10 years or so towards faster solution algorithms has been away from explicit methods, which are simple but time-consuming to apply, and towards methods with a higher and higher implicit content (the multi-grid method described below may be an exception). It appears that for rapid convergence a solution algorithm needs to allow disturbances to propagate over the whole flow field as rapidly as possible. The characteristics of the major solution algorithms are outlined below:

Explicit methods: During one time step in an unsteady problem, or one iterative cycle in a steady problem, information is passed from one point only to its immediate neighbors, so that many time steps or iterations are needed to propagate the information throughout the whole field. Numerically this manifests itself in a numerical stability condition which limits the time step length to small values. For the rest of this section only steady problems will be considered, although there is often a direct analogy between a time step in a unsteady problem and an iterative cycle in a steady problem.

Successive Line Over-Relaxation (SLOR): This has been the most widely used algorithm over the last ten years. Although considerably faster than explicit methods it is very much slower than the other methods outlined below. During each iterative cycle information is passed from a point to all other points on the same column, to all other points 'downstream' in the sweep direction and to a limited number of points 'upstream'. In a 2D problem with N points in the sweep direction it takes N iterations for information to pass from far downstream to far upstream. A converged solution will therefore take several multiples of N iterations.

Rapid Elliptic Solvers: After linearising the set of difference equations, formed by discretising the differential equation, by using values from the previous iterative cycle to evaluate the coefficients of the highest derivatives the solution at the new iteration level is obtained simultaneously for all points in the field. For simple elliptic equations this is probably the fastest method of all, but there are two important limitations: firstly, for mixed flows, the elliptic solver has to be alternated with some other method[31] such as SLOR, to achieve stability, and secondly it cannot be used when there are coordinate stretchings in all coordinate directions. If ways can be found around these limitations, the technique may prove to be attractive in the future.

Alternating Direction Implicit (ADI): For steady flows the ADI schemes are known as Approximate Factorisation (AF) schemes (see for example Ballhaus et al[32]). An iterative cycle involves sweeping in turn in each of the coordinate directions, so that information is passed throughout the whole flow-field during one cycle. The technique is much faster than SLOR and its only disadvantage is that more space needs to be used in the computer central random access memory than for SLOR; the storage of an array on backing store (disc or other sequential access medium) is likely to lead to unacceptably large input/output (I/O) overheads because the contents may need to be read in more than one sequential order. Nevertheless many arrays, such as transformation derivatives which do not need recomputing, may be stored in sequential access backing store, if necessary several times in different sequential orders.

Multi-grid: An iterative cycle consists of obtaining an updated solution on the computing grid by one of the above methods, then solving equations for the error on a series of successively coarser grids, (see for example reference 6). Much care needs to be taken in interpolating between successive grids but, because much less time is spent on each grid than on any finer one, an iterative cycle takes only about twice as long (at least on a scalar processor) as a single fine grid sweep. This technique promises to be even faster than the ADI methods. The explanation for the increase of speed seems to be that on each grid errors of wave-length comparable to the grid spacing are damped out, so that, for example, the finest grid is used to damp out small wave-length (or local) errors, whereas the coarsest grid is used to damp out large wave-length (or global) errors. Alternatively a coarse grid calculation may be viewed as enabling information to propagate globally while a fine grid calculation damps out local errors.

(ii) Finite element methods

Finite element methods are not so widely used as finite difference methods in computational aerodynamics. An explanation can be found in the fact that the Galerkin method from which most of the finite element methods start is actually well-suited to problems of elliptic or parabolic type. But these problems are only a few among those met in compressible fluid dynamics. And for the problems which belong to this type of equation (such as the full potential equation after linearization in the transonic regime or the incompressible Navier-Stokes equations) the use of finite element methods finds a full justification for complex geometries. Recently it seems that much work in computational aerodynamics has been devoted to improving the efficiency of computing methods to get results on simple geometries and little effort has gone into developing general methods for complex geometries.

However, interest is growing in finite element methods and mention can be made (in full potential transonic calculations) of the work of Eberle[33], Ecer and Akay[34], Deconinck and Hirsch[35], Vigneron et al[36] and Bristeau, Glowinski, Periaux et al[37]. Finite element methods seem to have reached a level of industrial 3-D application essentially with this latter team of workers from INRIA and AMD-BA.

As has already been said full potential (FP) and incompressible Navier-Stokes equations have been the two main subjects of application of finite element methods (FEM). However, only the former is sufficiently advanced to allow for a clear prediction of future computer requirements. For Reynolds Averaged Navier-Stokes equations only very crude estimations will be possible.

The capability of treating complex geometries by the use of FEM does not mean that mesh generation is straightforward. In the example of ref.13 the computational domain is filled with tetrahedrons. This is done either by subdivision of a regular hexahedral mesh analytically defined for the main part of the mesh or by an automatic but rather expensive process of building tetrahedrons in the remaining parts of the computational domain. Powerful graphical tools are needed for checking the mesh (and also for preparing the display of results).

In references 13 and 37 the nonlinearity in the FP equations is dealt with by least square minimization techniques. The conjugate gradient (CG) method with preconditioning is the major ingredient for solution of the problem.

The number of iterations needed to get convergence strongly depends upon the choice of the preconditioning operator. This number decreases with the implicitness of this operator whereas the storage needed increases in general. If a Laplacian matrix is chosen as a preconditioning operator, its Choleski factor contains a number of non-zero coefficients which is very much larger than both the original matrix and a well-defined incomplete Choleski factor. Clearly a compromise has to be made and incomplete Choleski conjugate gradient (ICCG) methods seem to allow a good balance between storage and computing time. Use of subdomains or blocks for dividing the computational region is likely to be used also in finite element methods for saving memory as well as for easier mesh generation. However special caution must be exercised to avoid slowing down the global convergence rate of the method.

(iii) Spectral methods

Since 1965 the Fast Fourier Transform technique has been developed (J. W. Cooley et al[38]). This has made possible the creation of a set of spectral (or pseudo-spectral) methods for unsteady viscous flow calculations. Periodic or non-periodic problems have been solved using Fourier or Chebyshev polynomial expansions. The main advantages of such methods are: for a given number of unknowns, the space accuracy is the optimal one, i.e. for the same accuracy, with the classical finite difference methods, approximately double the number of points are needed in each space direction; and for periodic problems the choice of Fourier expansions, and for non-periodic problems the choice of Chebyshev polynomial expansions, is optimal. One of the important applications of spectral methods is, for small Reynolds numbers, the direct simulation of turbulent flows within simple geometries: homogeneous isotropic turbulence in a cubic periodicity box[27]; homogeneous strain or shear turbulence[28]; and channel established turbulent flow[39]. Again within simple geometric domains, some simulations with a closure model for the subgrid scales have been performed for homogeneous turbulent shear flow and for channel established turbulent flow. For more complex geometries some new techniques are being developed but at present they are not efficient: mapping and connection technique for Poisson equation[41]; macro-element technique for Poisson equation[42]; and subdomain technique for 2D Navier-Stokes equations[43].

(e) Pacing Items

An attempt will be made here to indicate the areas where advances in numerical or modeling techniques most need to be made in order to produce the computer codes needed by aircraft and missile designers.

(i) Inviscid calculations: Here the most immediate problem is that of generating suitable coordinate systems. As indicated in Section (c) the most popular technique that is emerging is that of dividing the flow field into blocks with a different coordinate system within each block. In order to obtain a reasonable simulation of the flow at cruise adequate modeling of shock waves and vortex sheets is needed.

(ii) Thin shear layer calculations: Finite-difference, as opposed to integral boundary-layer methods, should improve the reliability of the viscous simulation. Improved turbulence modeling (as with ReA N-S equations) is needed, as is the treatment of mildly separated flows, shock waves, trailing edges, wakes, wing fuselage junctions and wing tips.

(iii) ReA N-S. All the advances mentioned in (i) and (ii) above are also needed for the ReA N-S approach. In addition the faster solution algorithms mentioned in Section (d) have yet to be applied to the 3D N-S equations.

(iv) LES N-S: Rapid solution methods are needed here before the LES approach for even simple flows can be used in earnest to provide information on turbulence modeling for (ii) and (iii) above. Improved sub-grid scale turbulence modeling is also needed.

2.1.4 Computer Requirements

(a) General Discussion

From the discussion in Section 2.1.3 it would seem that there are three areas where large scale computing facilities are needed for aerodynamic calculations:

(i) Interacting inviscid/viscous calculations for the simulation of flows about complete aircraft configurations at cruise conditions,

(ii) ReA N-S calculations for the simulation of flows about complete aircraft and missile configurations in manoeuvering conditions, and

(iii) LES N-S calculations for simple flow conditions to assist in formulating turbulence models for (i) and (ii).

It is thought that, for some time to come, calculation of unsteady phenomena arising from structural distortions (eg flutter, or for helicopter rotor blades) will be performed only on certain aircraft components, and so should not lead to an increased computer requirement (see section 2.1.2). Other types of unsteady flow phenomena will, of course, be included in time-dependent N-S calculations.

Chapman[7] has already given estimates of computer requirements in terms of memory size and speed (defined as the speed needed to complete a given calculation in one hour) and these estimates will be used as a starting point for the estimates made here. However, in the light of the review in Section 2.1.3 above, some modifications to Chapman's estimates will be made, leading to a reduction in estimated central random access memory requirement and an increase in estimated computer speed requirement.

Requirements for Finite Element and Spectral methods are discussed separately in Section 2.1.4 (d). They appear to be similar to those for Finite Difference methods covered in Section 2.1.4 (b) and (c) below.

(b) Memory Requirements

Total memory requirements for the three types of calculation mentioned in Section 2.1.4(a) are discussed in turn and the amount of central random access memory needed is then estimated.

(i) Inviscid/Viscous complete aircraft. Current FP wing/body codes utilize about $\frac{1}{8}$M grid points, and to represent the flow over a complete aircraft at least $\frac{1}{3}$M grid points will be needed. For a finite-difference solution about 30 quantities need to be stored at each grid point, including 27 transformation derivatives. As mentioned in Section 2.1.3 (d), these transformation derivatives may be stored in backing (ie sequential access) store, although, depending on the solution algorithm used, and on the block structure of the coordinate system, they may need to be stored several times in different sequential orders or partitions. The remaining quantities really need to be stored within central random access memory (RAM) to avoid unacceptably large I/O overheads. Allowing some additional space for other data, program, I/O buffers and workspace required by the computer's vectorizing compiler, a central random access memory size of 1.5M words is the minimum size needed for this type of calculation. For the viscous calculation, if performed independently of each inviscid iterative cycle, some use of the storage locations occupied by the inviscid data should be possible. However, to allow for the possibility of concurrent inviscid and viscous calculations an additional 0.5M words should be available giving a total of 2M words of RAM with upwards of 20M words of sequential access backing storage. On a grid of the same size an Euler code would require more storage, since there are more dependent variables to store at each point, so that a total of 6M words of RAM may be needed.

(ii) ReA N-S complete configurations. Chapman[7] estimates a total memory requirement of about 100M words for a Reynolds number based on wing chord of 10^7. Use of sequential access backing store could reduce the central random access memory requirement to 10M words.

(iii) LES N-S aerofoil. In order to simulate the essentially 3D nature of turbulence Chapman[7] bases his memory estimates for the calculation of the flow over an aerofoil on the requirement to model the flow over a span of about 1/5 chord in order to avoid edge effects, but with the Euler equations used over the outer 99% of the overall turbulent layer thickness and with turbulence modelling used in both the sub-grid scale and viscous sublayer. He estimates a memory requirement of 300M words for $Re = 10^7$. This requirement grows considerably if viscous sublayer turbulence is to be computed. It is difficult to estimate how much central random access memory is needed for this calculation, but with ingenuity it might be possible to limit it to 10M words as for (ii) above.

To summarize it would appear that the very minimum practical central random access memory sizes needed for the three types of calculation are 2M to 6M words for type (i) and 10M words for types (ii) and (iii) above.

(c) Computer speed

Computer speeds used below are expressed in Mflops, (millions of floating point operations per second) and the speed needed is defined to be that needed to complete the given calculation in one hour's processing time.

(i) Inviscid/viscous complete aircraft: Current FP wing/body codes need computer speeds of about 2Mflops. When viscous effects are added this increases to about 3Mflops. Algorithm improvements could reduce this to 1Mflops within the next few years. However, if the number of grid points is increased to model the complete aircraft the required speed is likely to increase by a far greater factor because the fast solution algorithms will be much less effective if the computational domain has a highly irregular shape. If the computational region is divided into blocks, and if, during one iterative cycle, the solution algorithm is applied in turn to each block, the number of iterations to achieve convergence could rise by a factor in excess of the number of blocks, compared to that needed if there were only one block covering the whole field. It is possible that solution algorithms will be developed which allow information to pass rapidly between blocks. Nevertheless, considering that there are likely to be in excess of 100 blocks for a complete aircraft, it does not seem unduly pessimistic to assume that the number of iterative cycles needed for convergence will increase by a factor of 10 because of the use of multiple blocks. Hence, for a complete aircraft, computer speeds of at least 30Mflops are likely to be needed. Another effect of a multiple block structure is that vector lengths are likely to be reduced, so that the ultimate speeds of vector machines may not be realized. The solution algorithm itself affects vector length greatly. Vectors will be long for ADI methods, but for multigrid methods will decrease for the parts of the calculation on the coarser grids. According to Ni[6], Euler codes need take no more than 2.5 times as long as FP codes for the same grid in two dimensions. Thus, assuming that this factor may be applied also in three dimensions, and scaling up the inviscid but not the viscous element of the requirement, for Euler codes computer speeds of about 60Mflops will be needed. This is about 10 times the required speed estimated by Chapman[7] for inviscid calculations, say 7 times for the inviscid/viscous interaction.

(ii) ReA N-S complete configurations. Chapman estimates a required computer speed of over 10^3Mflops. With the same arguments as above this requirement could increase to 10^4Mflops.

(iii) LES N-S aerofoil: Chapman estimates a required computer speed of 10^4Mflops. Since only one block is needed for this simple case there is no need to change this estimate.

(d) Finite Element and Spectral Methods

(i) Finite Element Methods: Owing to the small number of practical users of finite element methods for aerodynamics computations, it would be somewhat hazardous to give a precise prediction of future computer requirements in this field. More generally, it must be stressed that the efficient use of a large scale computer near the limits of its capabilities requires a careful adaptation of the solution method and of the program coding to the computer architecture. For example, it is highly desirable to achieve a correct overlapping of data transfer with computations and to detect in the algorithm all the usable parallelism. This means that, apart from the situation where central memory capacity and floating point scalar processing speed are clearly sufficient for handling a problem, the definition of memory and speed requirements should be supplemented by information about other parameters of the configuration such as the I/O transfer rate and the influence of the length of vectors on the computing speed in vector mode.

Therefore, only a crude estimation is attempted for the calculation of inviscid flows about a complete aircraft at cruise conditions. The computation already cited[13] corresponds to about 10^4 nodes. This leads to linearized systems with matrices of 10^5 non-zero coefficients and Choleski factors of 3 Mwords. Mass storage on disk is used and the reduction of CPU time to one hour would require a computing speed of about 6 Mflops.

It is thought that 10^5 nodes would suffice for a sufficiently accurate simulation of the inviscid flow with a highly stretched mesh of tetrahedral elements. The size of the matrix would be 1M words with a Choleski factor of 30 Mwords. It could be preferable to use an incomplete Choleski factor with 1.5 M non-zero coefficients, then the global memory requirement would be decreased to 3M words. As concerns the speed needed for a one hour computation, an increase by a factor 10 would give 60 Mflops. It is likely that improvements in the solution method will reduce this value but conversely the coupling with a viscous boundary layer could need extra work corresponding to a multiplicative factor of about 1.5 for a weak coupling.

About Navier-Stokes equations it can be said that the amount of memory needed per node is not very different from the inviscid FP case. However, for the same number of nodes the computing time is increased by an order of magnitude. Since the mesh must be very much finer near the solid walls and in wakes it is not unlikely to require an increase by a factor of 10 in the number of nodes. When compared with the FP equations a very crude estimation could be an increase by a factor of 10 for the total memory and by 100 for the computing speed needed.

(ii) Spectral methods: We can choose as two very interesting examples the methods developed by R.S. Rogallo[28] for the homogeneous turbulence and by P. Moin et al[39] for the channel flow. All these estimations will be done for a CRAY-1 computer (1 Mwords for central memory and 80 Mflops for speed). Today with 64^3 (252 K) harmonics at least 3.2 Mwords are necessary and we need, for 5,000 time steps: 4 hours of CPU time and 11 hours of I/O time for the simulation of anisotropic homogeneous turbulence; and 8 hours of CPU time and 22 hours of I/O time for the channel flow calculation[39]. For a better approximation of the numerical solution 128^3 (2M) harmonics and 26 Mwords would be necessary. So with a CRAY-1 computer an evaluation of the cost of 10,000 time steps can be obtained: 120 hours for the CPU time, 400 hours for the I/O time (homogeneous flow[28]); and 240 hour for the CPU time, 800 hour for the I/O time (inhomogeneous flow[39]). Such simulations would become practicable if a large reduction of the CPU and I/O time were possible. A speed of 8000 Mflops and a central core memory of 32 Mwords would give 1 hour of CPU time and "no" I/O time (homogeneous problem).

About subdomain techniques for solving Navier-Stokes equations within complex geometries it can be said that they are not yet optimised and that no estimation can really be made.

2.1.5 General Remarks

This brief review considers the application of large-scale computing to the aerodynamic aspects of aeronautical R and D covering the topics: Aerodynamic flows about practical configurations; fundamental understanding of fluid dynamics and acoustic phenomena including atmospheric turbulence (the interest in the last being primarily to meet the need to understand the influence of atmospheric phenomena on aircraft behavior); and wind tunnel testing.

It is argued that in practice aerodynamic flows about practical configurations is the dominant topic. Current methods have demonstrated, in the applications for which they have been developed, the very large economies they can bring to aircraft design, in reducing the costs of wind-tunnel testing and in the concomitant reduction of the time scale required to provide a final design. For the future the development of methods to deal with flows of greater complexity than hitherto possible and, to deal with the geometry of complete configurations, will require greater computer capacity than is generally available. The future methods are visualized as not only providing predictions of greater reliability for the basic flight condition of cruise but also of assessing characteristics for manoeuvre conditions of both aircraft and missiles. In assessing the computer requirements for these methods it is supposed that Reynolds-averaging for the turbulence properties of the flow will be utilized; the requirements would be increased enormously if the aim were to limit the turbulence modelling to the smaller-scale eddies (LES); an example is given for the requirement for a basic two-dimensional flow.

Table 1 summarises the various estimates of compute requirements which have been made in this report. Basically the requirements (based on the requirement to complete a given calculation in 1 hour's computation time) are:

(i) For the numerical simulation of flows around complete aircraft configurations at cruise a sustained computational speed of 30-60 Mflops (floating-point operations per second) and a minimum central random access memory size of 2M to 6M words is needed. A further 20M words of sequential access backing storage will be needed. This requirement can be provided by current Class 6 machines.

(ii) For manoeuvring aircraft and missiles the requirements for speed and memory rise respectively to 10^4Mflops and 10M words of central random access memory plus 100M words of fast sequential access backing storage.

(iii) A similar capability to (ii) is required to develop LES codes for basic two-dimensional flows as an aid in assessing and extending turbulence modelling, although the fast sequential access backing storage requirement could be three times that of (ii).

The requirement for (ii) and (iii) implies a computer with central random access memory capacity somewhat less than the proposed NASA NAS but with a speed about 10 times greater.

These estimates do not take account of the possible use of flowfield methods as modules in other calculations such as response and load analysis of aircraft in conditions of turbulence. If it were necessary to use them in this way in order to take account of the non-linear nature of transonic flows, increases in speed beyond those quoted would be required. It seems likely, however, that even if it were desirable to account for non-linearities of the basic flow for a given datum condition, the perturbations from the datum could be treated as linear and the demands on the computer would then not rise excessively. The interaction of aerodynamics, dynamics and structures in this context is addressed in Section 2.5.

It should, perhaps, be noted here that the 1 hour run times referred to above apply to the simulation of the flow about a single aircraft or missile configuration for a single set of flight conditions. Many runs could be needed to cover a range of flight conditions, and for design/optimization type computations. For example, 3D wing design by means of numerical optimization requires of the order of several hundred direct flow computations[44].

A computer of the power and size necessary for (ii) and (iii) above could additionally be used for related applications. Examples of such applications are: the achievement of more efficient use of wind tunnel testing time through real time computation enabling test conditions to be changed rapidly; the modelling of turbulent noise sources and the non-linear propagation of noise through shear flows; and the modelling of local weather conditions in the vicinity of airports as a means of predicting specific phenomena (eg severe shear layers) based on a few ground measurements.

TABLE 1

ESTIMATED COMPUTER REQUIREMENTS FOR VARIOUS TASKS

Problem	Flow Equations	Discretisation Method	Speed (M flops*) for calc. within 1 hr	RAM	Fast Sequential Access Memory
Helicopter rotors	Inviscid/viscous interacting	Finite Difference	10-20	5M	10M
Complete aircraft at cruise	Inviscid/viscous interacting	Finite Difference	30-60	2-6M	20M
Complete aircraft at cruise	Inviscid/viscous interacting	Finite Element	60	3M	30M
Complete aircraft at cruise (unsteady)	Inviscid/viscous interacting	Finite Difference	60-120	6M	40M
Manoeuvring aircraft /missile	ReA	Finite Difference	10000	10M	100M
Manoeuvring aircraft	ReA	Finite Element	6000	30M	300M
Low Re Homogeneous turbulence	Incompressible NS	Spectral	8000	32M	-
'2D' Wing	LES	Finite Difference	10000	10M	300M

*For reference a CDC 7600 could operate at about 5 M flops, while current Class 6 machines easily maintain rates above 20 M flops, with a theoretical upper limit of 800 M flops. NASA have prescribed a sustained rate of 1000 M flops for the proposed NASF.

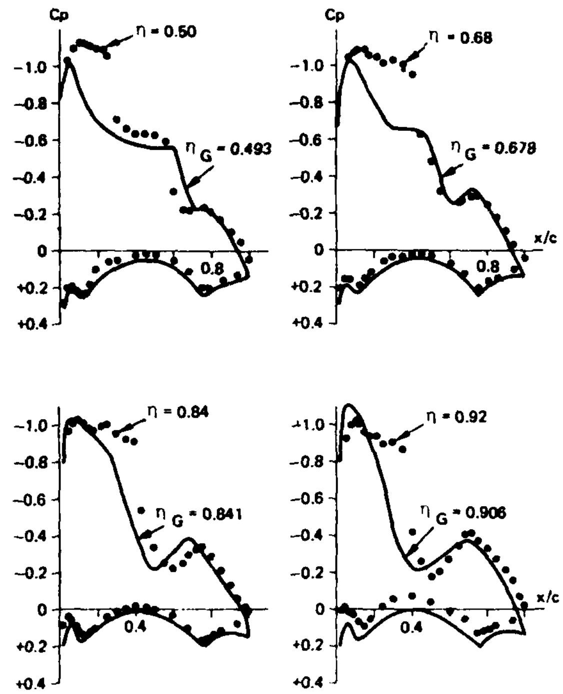

Fig.1a Pressure distributions at M=0.88 for Design Point 1

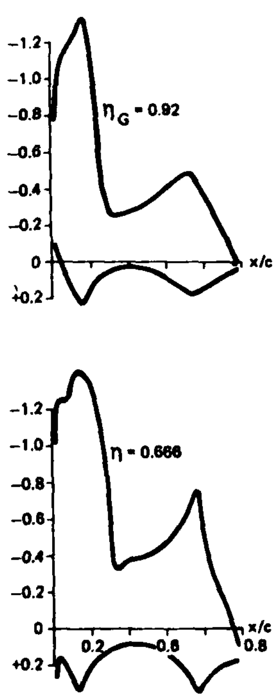

Fig.1b Pressure distribution for Design Point 3

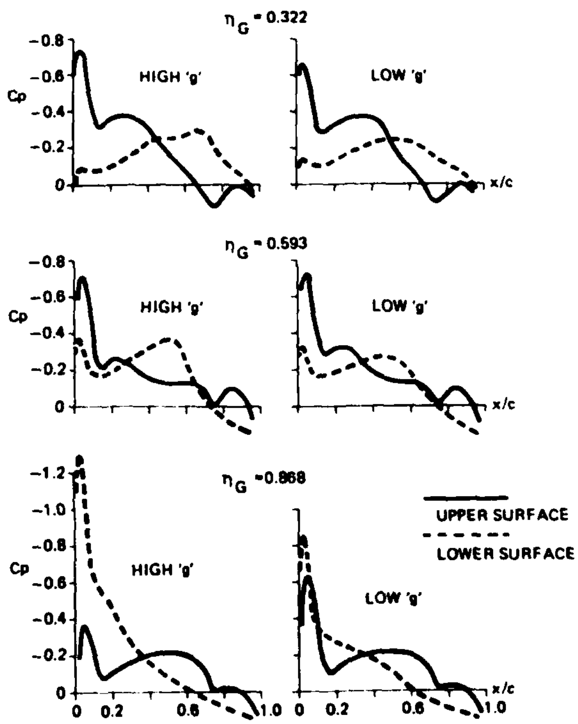

Fig.1c Pressure distribution for flap deflection -5/-4 for Design Point 2

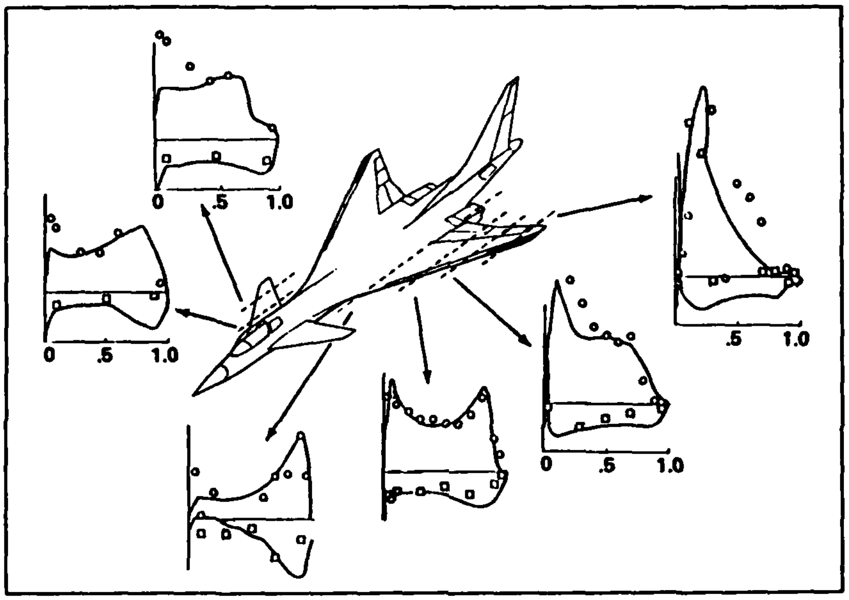

Figure 2 Wing-Body-Canard Pressure Distribution Correlation ($M= 0.90$, $C_L \sim 0.67$)

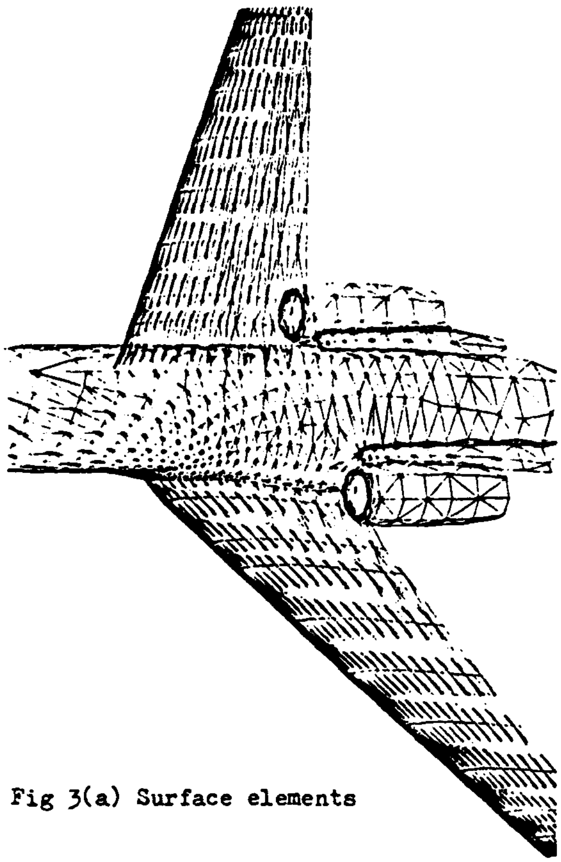

Fig 3(a) Surface elements

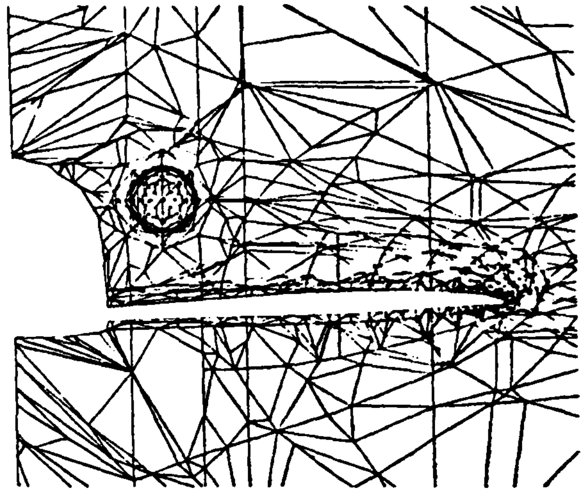

Fig 3(b) Section normal to plane of symmetry showing elements in the flow field

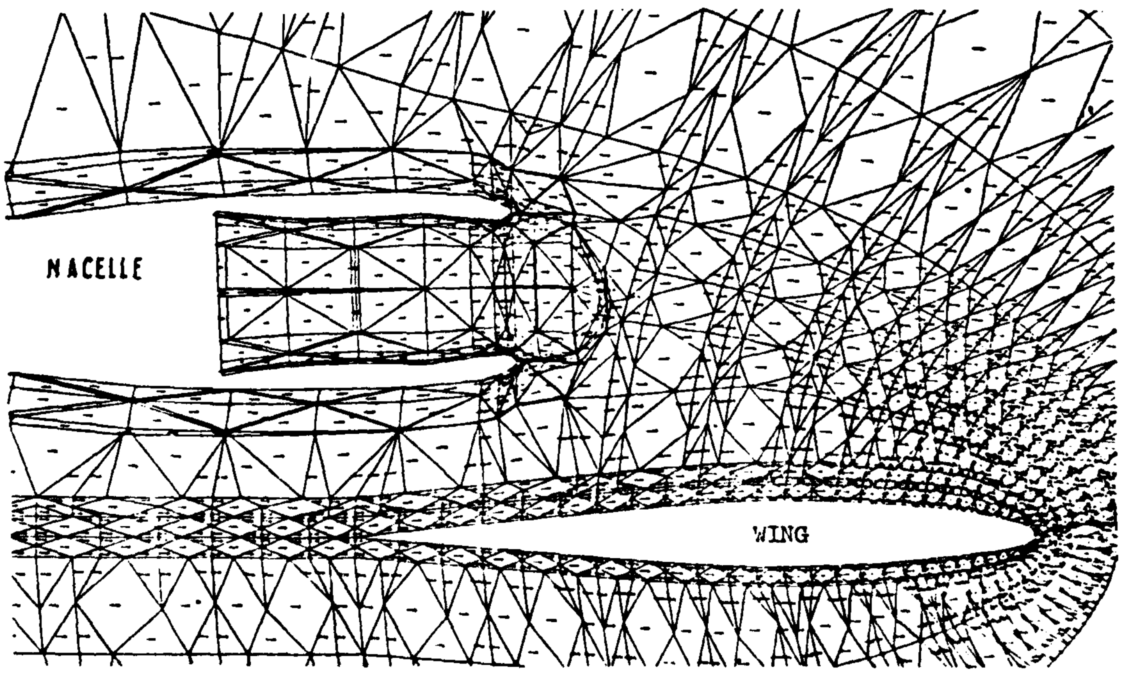

Fig 3(c) Section parallel to plane of symmetry showing elements and velocity field

Fig 3 Finite element grid on FALCON 20G (reproduced from ref. 13)

Civil aircraft

1. Economical cruise at one speed
2. High aspect ratio monoplane, producing vertical lift force efficiently (low induced drag)
3. Very accurate aerodynamic data required over limited range of conditions
4. Max g ~ 2

Missiles

1. Highly manoeuvrable over a wide speed range
2. Cruciform low aspect ratio wing-body-control combination able to develop lateral force in any direction
3. Aerodynamic data required over a wide range of incidence, roll angle and Mach number
4. Max g ~ 5-50

Fig.4 (from Ref.17) Aerodynamic differences between civil aircraft and missiles

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2.2 Structures and Materials

2.2.1 Introduction

The design of fail-safe, minimum weight structures is a topic which has intrigued aircraft engineers since the beginning of powered flight. With the advent of digital computers, new possibilities became available and continuous improvements in computerized structural and materials analyses have been made along with the general progress in computer development. More or less sophisticated and refined computer programs are now available to all aircraft companies and are used routinely in the design of major aircraft assemblies.

By way of illustration, the present state of the art in computerized structural analysis and the widespread application of computers in aircraft structural design are shown by the well-known computer code, NASTRAN. In 1970, there were 50 computer sites with about 900 employees using NASTRAN. By 1979, usage had increased to 265 computer sites with 2600 users[1]. This increase was due primarily to the general capabilities of the software and its continued maintenance as a state-of-the-art finite element computer program.

With a range of computer programs for individual structural design purposes at hand, the need for automated design and structural optimization has evolved, and in the past two decades great effort has been devoted to the creation of structural optimization programs. In addition, considerable effort has been expended on the prediction of material properties in the failed state in order to fully utilise cracked or buckled structures using metallic or composite materials. The advent of large digital computers, together with the continuing development of the finite element technique and the application of pre-and post-processors and interactive capability, have led to considerable progress in integrated computerised structural design in the past decade. It is the primary purpose of this section to forecast applications and possible benefits of "super-computers" in aeronautical structures and materials research and development by assessing the current status of computational structural mechanics and discussing potential future developments.

First, some general remarks will be made concerning typical applications of computers including optimization of structural and material properties, structural analysis and design methodology and the analysis and modelling of fatigue phenomena. Second, a review will be made of the current status of computer resources brought to bear on these applications, and some forecasts made about the likely future trend of computing in the structures and materials area. Third, those structures and materials applications which are likely to benefit most of all from the availability of more powerful computers are described, leading to some specific computer performance requirements. Finally, some estimates are made of the potential demand for more powerful computers.

Throughout, use has been made of responses to a questionnaire which was circulated to Industry, National Research Establishments and Universities throughout the AGARD community. Information was provided by 40 contributors in 8 AGARD countries.

2.2.2 Current Status of Computer Applications

(a) Structural Analysis

(i) Static stress and strength computations

In static stress and strength analyses of aircraft structures and structural components, the finite element (FE) method as well as the finite difference (FD) method have proved to be efficient tools in solving a wide range of structural problems. Application of the FE method leads to the well-known stiffness matrix approach of structural analysis[2]. Once the solution of unknown displacements has been obtained from the solution of a corresponding system of algebraic equations, the stress and internal forces of each element can be computed. In the case of nonlinear constitutive relationships a solution can be obtained using a tangential stiffness matrix with either the initial strain or initial stress method. Large deformations are taken into account by continuously updating the nodal point coordinates and thus by using actual stiffness relationships. Special procedures are applied to handle large strains. The FD method has its origins in the governing differential equations of the problem which are approximated by the corresponding difference equations. The resulting set of "finite" equations can then be defined in a system of uncoupled algebraic equations for the unknown parameters. For the solution of static stress and strength problems of complex aircraft structures the FE method has proved to be the more flexible approach since it allows use of different types of elements, leading to high computational accuracy of the stress and strain fields in the structure. Moreover the FE method permits unconstrained consideration of arbitrary structural configurations with any boundary condition. However, in those cases where the structural problem can be formulated adequately in terms of differential equations with clearly defined boundary conditions the FD method has its advantages, at least with respect to computer costs and computing time, when elastic-plastic and nonlinear effects with large displacements and large strains are to be taken into account.

Both the FE method and the FD method have their fluid dynamic counterparts in the well-known panel methods and in the finite difference algorithms applied to solve the Navier-Stokes differential equations. Therefore, from a computational point of view much of what is stated in the Fluid Dynamics discussion (Section 2.1) applies also to static stress and strength computations of complex structures. With the present class of computers, (linear) FE analysis of structural models containing more than 3000 finite elements are possible which seems sufficient for most practical applications. A typical example of such an FE approach for the structural design of an aircraft wing is illustrated in Figure 1. However, as composite materials are applied extensively to primary structures of aircraft, missiles and spacecraft in the near future, computer requirements will surely increase and better computerized tools for the performance of structural analysis will be needed.

(ii) Static structural optimization

With the developments achieved in computerized structural analysis, where a range of computer programs is available and used routinely in the design of major aircraft components, the need for an automated design or structural optimization has evolved. Structural optimization in aircraft design generally means weight minimization of a finite element model with (aerodynamically frozen) fixed geometry and material properties. It includes interaction of the external shape, aerodynamic loads, structural geometry, internal loads and fuel mass to arrive at a fully stressed yet minimum weight design of an airframe structure. The corresponding cyclic design process of an aircraft structure for a given fixed external shape, when only static or quasistatic constraints are taken into account, is schematically shown in Figure 2. The optimization process is based on structural strength, wherein the mass of the structure is minimized subject to the requirement for sufficient strength to carry the external (quasi static) design loads. The resulting design of such an automated static structural design process, as widely applied in modern aircraft development, is generally referred to as a "Fully Stressed Design". Experience has shown that such a design closely approximates, but does not necessarily yield, the minimum mass structure. Computer requirements for this automated (static) structural design process can be satisfied by conventional computers and/or array processor augmentation with associated algorithm and software development. For instance, for the optimum design of an aircraft wing, up to 5000 degrees of freedom together with up to 100 opitmization parameters and up to 200 static constraints (see Figure 1) can be handled with conventional mainframe computers which satisfy almost all requirements from the standpoint of practical application. Insofar as the aerodynamic module of this optimization process is concerned, the computer requirements and related computer codes are basically the same as for steady potential flow calculations using panel methods.

(iii) Aeroelastic and dynamic response investigations

Important fields of computer application in aircraft design and development are those of structural dynamics and aeroelasticity. In these fields, knowledge of the characteristic vibration behaviour of the airframe in terms of modal vibration parameters (such as normal frequencies, normal modes and related generalized masses) is a prerequisite for performance of structural dynamic investigations. For aeroelastic stability and dynamic response investigations, adequate knowledge of the motion-induced unsteady airloads is an additional prerequisite.

Computer requirements for the preformance of modal vibration calculations of complex aircraft and spacecraft structures, based on finite element models and applying matrix methods, are practically the same as for static stress and strength calculations. However, for the solution of dynamic structural problems involving elastic-plastic flow with large displacements and strains, including nonlinear effects, Finite Difference methods based on direct integration of the governing equations of motion may also yield acceptable solutions at significantly lower cost than with an FE approach.

When the governing aeroelastic equations of motion are assumed linear, structural dynamics terms and unsteady aerodynamic terms can be handled independently within the framework of linearized structural and aerodynamic theory. Then, by applying the principle of superposition (and with the further assumption of harmonic motion), one arrives at relatively simple linear equations for the solution of aeroelastic stability or dynamic (aeroelastic) response. The crucial point and most time-consuming task of aeroelastic analysis is a determination of the unsteady airloads of the oscillating aircraft. However, when classic aeroelastic problems associated with potential flow are investigated, unsteady aerodynamic calculations performed as part of dynamic aeroelastic studies can be executed adequately with conventional computers. Performance of these aeroelastic investigations with more than 20 simultaneous degrees of freedom (mode shapes) has become a routine task in aircraft design and development.

In developing modern combat aircraft to operate in transonic and post-stall flight conditions, aircraft designers are faced with new aeroelastic problems. Separated-flow unsteady airloads as well as transonic airloads exhibit highly nonlinear behaviour regarding the steady mean angle-of-attack and the amplitude of oscillation. Thus, the concept of linearity, which has served aeroelasticians well in solving the majority of classic potential-flow aeroelastic problems, can no longer strictly be applied to aeroelastic studies in the transonic regime, or wherever flow separations play an important role.

Such nonlinear aeroelastic analyses are currently still in the preliminary stage but there is no doubt that the availability of a more powerful computer would allow more exact theoretical solutions to be derived. Specific computer requirements for unsteady airload calculations for transonic and/or separated flow conditions will be basically the same as those indicated in the Fluid Dynamics discussion (Section 2.1) in the context of prospects for computing viscous flows. In addition, computer memory and speed requirements for simultaneous solution of the structural equations based on Finite Element modelling are expected to be twice as high as for the solution of the flow equations alone.

Computer requirements for the performance of aeroelastic and dynamic response analyses of rotary wing aircraft, taking into account transonic and viscous flow aerodynamic effects, are expected to be even greater than for fixed-wing aircraft. This is due to the fact that, in addition to aerodynamic nonlinearities, gyroscopic coupling effects and structural nonlinearities may play an important role in overall aeroelastic stability. Symbolic mathematical computation[3] may aid considerably in the performance of rotary wing aeroelastic analysis.

(b) Materials Analysis

(i) Fracture mechanics

Where a structure may fail due to cracking of the material, in some cases cracks can be allowed to appear and grow before a critical size is reached, the period prior to initiation and the subsequent subcritical growth being the lifetime of the structure. This has led to the concept of "damage tolerance" used in the certification process of airplanes and in this case the structural integrity has to be assessed in the presence of a crack. It has been shown[4] that the presence of a crack in an elastic structure under loading results in singular stress and strain fields at the tip of the crack. The solution of the problem is given in the form of a series expansion for these fields, the first term exhibiting a singularity in $r^{-1/2}$, r being the distance from the crack tip. The coefficient of this term, the Stress Intensity Factor (SIF), has been proved to be of great practical importance in either predicting sudden rupture (when it reaches a critical value), or in describing the crack growth rate (through Paris-type laws[5]). Consequently, several numerical methods for computing the SIF have been developed, since analytical expressions can only be derived in a very restricted number of "academic" cases. They are based primarily on the Finite Element approach, although, in recent years, Boundary Integral Equations also have proved to be a valuable tool. Starting from a "classical" analysis of the cracked structure (giving as results the displacement, strain and stress fields) several approaches lead to the SIF including "local" techniques such as the smoothing of displacement, strain and stress fields using analytical expressions, and "global" energy techniques[6], or perturbation methods[7] using the relation between the SIF and the Griffith parameter. These numerical analyses have become current practice in aeronautical design. However, they are very time consuming (either from the point of view of CPU or data preparation times) due to the fact that very refined meshes are required to describe the singularity in the vicinity of the crack tip. Typically, 3000 degrees of freedom and 600 elements are needed for a 3-dimensional analysis of a linear structure.

(ii) Damage mechanics

In some cases the appearance of a crack must be avoided, since it can lead very quickly to a catastrophic rupture. This is the case, for instance, in turbine or compressor discs where rupture produces high kinetic energy fragments able to cause very severe (and even catastrophic) damage to the aircraft structure. Methods have been developed recently which solve the problem of crack initiation prediction. Since, by hypothesis, no crack exists when the life of the structure starts, the SIF is of no use in this case. The basic idea of Damage Mechanics[8] is introduced by the damage parameter. Physical observations have shown that before the appearance of a single macrocrack (say of some tenths of a millimeter long), many microcracks or microvoids are observed at grain boundaries or inside the grain itself. Consequently, the net section (or active section) is reduced and the effective local stresses can be higher than the "apparent" ones computed using the initial section. Because of stress concentration, the amplification factor is generally greater than the ratio of sections and this leads to the allocation of a damage parameter, to each volume element of material, of zero initial value but reaching a critical value of one when the microcrack appears in this element.

This damage parameter, D, is understood as an internal state variable (in the thermodynamic sense) and must be associated with an evolution equation in order to describe its variation between 0 and $D_{critical}$ (generally taken equal to 1.0). In fact, two main physical mechanisms have been identified for creating microcracks and microvoids, creep and fatigue, each of them being characterized by the specific aspect of the damage it produces. It follows that knowledge of the "damage law" is required in order to predict crack initiation and this, in turn, demands the precise definition of stresses and strains throughout the structure. Moreover, the process of initiation is often associated with high temperature environments and the subsequent non-linear behaviour of the material. As a consequence of the very strong non-linearity of the problem, powerful computers are necessary to perform this kind of analysis.

(iii) Buckling and post-buckling

A structure may fail, even if no part of it is cracked, when buckling occurs locally or on the whole structure. It can be of interest to define the residual strength after buckling in order to determine, for instance, the load transfer from the collapsed part to other components, or a safety factor. This kind of analysis is known as "post-buckling" analysis, and is characterized by: large strains (at least locally) that mean that the non-linear term of the strain tensor has to be retained, different possible behaviours for the material (linear elastic, non-linear elastic, plastic) and the use of numerical methods, mainly Finite Element, using the displacement method.

Although the geometry undergoes large changes during the process, a Lagrangian formulation is generally preferred. The time-consuming nature of the non-linear computation together with the computer limitations currently encountered restrict analyses to simple structures, although more complex ones are of interest; for example, stiffened panels with assemblies.

2.2.3 Current Status of Computer Resources

(a) Configurations

Computers used in structures and materials range from midi-computers (< 1 Mflops), through to conventional mainframes (< 10 Mflops) with an overall capacity which is in broad relation to the size and status of the parent organization. The organisational stereotype operates one or two conventional mainframes with batch working overnight and distributed terminal access by day; some have access to a Class 6 computer (> 100 Mflops). Almost without exception, users seek improvements at all levels of computing, in all disciplines and in all environments!

(b) Capacity

Improvements in computing capacity are advocated either because it is impracticable or uneconomic to derive the particular solution required on the available computer resource even if it were fully dedicated to that task, or because the number of users requiring a share of the available computer resource, even with the best site management, leads to an unacceptable service for the majority. These deficiencies can be corrected by additional or by more powerful computers, by displaying ingenuity in developing new algorithms, and by using engineering judgement to retain realism while solving a more approximate model of the physical system.

In the structures and materials community, some users would benefit from super computer access. However, the majority seek improvements which can be satisfied by additional resources up to Class 6 computers. For the latter, it is important to identify peripheral improvements which are needed to enhance the computing environment and which might reasonably be expected to apply to all computers.

(c) Peripherals

Improvements in computer peripherals are advocated principally to enhance the interactive computing role. In our organizational stereotype, supported by company mainframe computers, the following improvements are advocated: more extensive and responsive terminal screens and printers to provide the engineer with a productive computing resource at his fingertips, and improved terminal graphics and colour facilities to develop the effectiveness of this resource. There is an increasing need, as solution methods become more complex, for interpretive procedures which digest output data.

(d) Software

Computer networking is advocated, to provide mini - or midi - computer pre- and/or post-processing of mainframe data, or to provide a link between different functions in an integrated design environment. The related computers, having been introduced in isolation, may well be of different manufacturing origin, thus compatibility of software on the networked machines needs to be ensured. Array processing is widely advocated, and add-on extensions are available for most conventional mainframes. Once more, apposite software needs to be developed to realize the full benefits in solution times.

(e) Cost

Aside from, but clearly related to, technical considerations many users advocate reductions in the costs of all aspects of computing. While highlighting the very important element of cost this attitude also carries the imputation that available resources are broadly adequate in technical capability. Probably this reflects the tradition in structures and materials activity, paralleled across all aeronautical disciplines, of developing available models which sacrifice complete rigour in the basic mathematical description but which are cost effective to use and which suffice via empirical adjustments acquired over the course of experience. There is no doubt that the applications of supercomputers must generate sufficient confidence in more realistic modelling to pay off in reduced proving trials on the product. This attitude will continue to be manifested in an apparent reluctance by the user community to embrace new theoretical methods until cost effective applications have been proved. This aspect will be important in any judgement of demand.

(f) Likely Future

The likely future in structures and materials shows computing developments over a broad front, embracing Class 6 computers and at least preliminary applications of supercomputers. Emphasis is placed upon improving the interactive role of conventional mainframe computers, developing integrated design methods, utilising array processor augmentation, provision of adequate software, and reducing the cost of computing. Throughout, cost must be the overriding consideration and it should be recognised that the improvements advocated here are advocated by users and do not necessarily represent organisational policy. It is clear that very few users in structures and materials see a driving need for a super-computer specifically for their needs.

Although a driving need is not established, there is little doubt from past history that a supercomputer will be used in structures and materials applications if it becomes available and if it is economically viable for the organization wishing to utilise it. Equally clearly it is probable that early users will involve some short tentative research assessment; full acceptance by the design community will not follow for some time, until adequate proving trials have been completed. The technical activities in structures and materials which look most likely to benefit from computing resources beyond Class 6, i.e. supercomputer capability, are interdisciplinary optimization and non-linear structures and materials analysis. In order to assess potential demand it is useful to review the technical requirements in more detail.

2.2.4 Applications of Supercomputers

(a) Interdisciplinary Optimisation

The structures of most aircraft developed in the past have been optimized for purely static considerations. Dynamic response and aeroelastic investigations have been performed more or less a posteriori for a structurally and geometrically (i.e. aerodynamically) predesigned system for aeroelastic and dynamic qualification of structural design. Presently great efforts are being made to develop computer program systems capable of performing interdisciplinary optimization by taking into account both static strength and dynamic aeroelastic constraints and to include transonic and/or separated flow unsteady airloads with active controls. The need for such an interdisciplinary structural optimization has received added emphasis from the increasing and advantageous application of composites in aircraft design utilizing "aeroelastic tailoring". The flutter and strength optimization program FASTOP[9], developed some years ago, documents the present state of the art. However, with regard to the power of Class 6 or supercomputers, new possibilities in interdisciplinary optimization are emerging.

(i) Simultaneous inclusion of static and dynamic aeroelastic constraints

A functional flow diagram of an interactive static and dynamic structural optimization process taking into account aeroelastic constraints is presented in Figure 3. Solid lines indicate those portions of the process based on static structural strength with regard to minimum-weight design. Dotted lines show the additional considerations of static and dynamic aeroelasticity, both of which depend on the stiffness of the structure. The ideal computerized structural design systems would automatically carry out various stages of this process leading to a final weight-optimized structural configuration. Generally, such a computer code (e.g. FASTOP) is comprised of two major programs which are executed consecutively, a strength optimization program and an aeroelastic optimization program, each program designed to perform successive analysis and resizing functions in a single computer submission. The first one is focused on basic aspects of static FE element structural analysis and minimum-weight design for strength requirements.

The computer code prepares all structural data required for direct input to the second major program, namely the structural mass and stiffness matrix for vibration mode analysis. With these inputs at hand, the aeroelastic optimization program computes normal mode shapes and frequencies (and hence the related unsteady airloads), determines the critical flutter speed and performs (if necessary) resizing to increase the critical flutter speed. With the stiffness properties and steady airloads, static aeroelastic effects (static divergence and changes in aerodynamic loading resulting from lifting surface deflections) are computed in parallel. Finally, the aeroelastic optimization program saves data required for reentering the strength optimisation program.

Currently in aircraft design and development, such interdisciplinary structural optimisation has been applied mainly to specified lifting systems, such as wings and tailplanes, (see Figure 1). When the aeroelastic optimisation program is based on a classic-type (potential-flow) flutter analysis, such interdisciplinary optimisation can be performed with presently existing computers to meet all practical requirements. Interdisciplinary structural optimisation of the complete aircraft by simultaneous inclusion of static and dynamic aeroelastic contraints is rather prospective at the present time, but desirable.

(ii) Inclusion of transonic flow unsteady aerodynamics

Aeroelastic problems often become most critical in transonic flow conditions. This is reflected for instance in the flutter behaviour of a swept wing as shown in Figure 4 where the so-called "transonic dip", a region of relatively low flutter speed in the transonic flight regime, is plain to see.

As mentioned previously, the computer capacity required for aeroelastic analysis is basically governed by the requirements for predicting unsteady airloads. In the subsonic and supersonic flight regimes the motion-induced unsteady airloads of oscillating lifting systems can be predicted reasonably well for aeroelastic investigations by applying linearized (potential-flow) lifting surface theory and using conventional computers. Such calculations however require much more computer capacity in the transonic regime for two reasons. Firstly, nonlinear flow equations must be solved, applying at least the small-disturbance nonlinear potential equation, where the degree of complexity depends a great deal upon the amplitude, frequency or time scale, and the strength and movement of the shock waves. Secondly, owing to the nonlinear aerodynamic behaviour of unsteady transonic flows, the structural equations must be solved simultaneously with the flow equations, abandoning the concept of superposition of normal modes. Performance of such a nonlinear aeroelastic flutter analysis for the transonic flow regime itself is already a formidable task, the solution of which is presently rather prospective and is indeed a challenge to aeroelasticians. Inclusion of transonic flow unsteady aerodynamics in interdisciplinary structural optimization is even more complicated. Conceivably a supercomputer may be the ultimate key to success. However, at the present stage of knowledge and experience it is difficult to make any statements concerning detailed computer requirements for the future.

For a helicopter rotor blade in combined rotational and translational motion there are three main factors that complicate the unsteady transonic flow problem beyond that for the fixed-wing aircraft. In the first case, the amplitudes of incidence and lift fluctuations are generally too large to invoke the linear unsteady perturbation concept. Secondly, the local Mach number increases with the distance from the axis of rotation, thereby accentuating transonic effects near the tip and interacting with the tip vortex effect. Finally, the local blade incidence and local Mach number both vary harmonically, approximately 180° apart in phase. At present, this three-dimensional unsteady rotor case remains an untouched problem in the transonic regime. Solution of the nonlinear transonic rotor blade flutter problem and its inclusion in an automated structural design process is extremely problematic not only because of the nonlinear feature of the unsteady airloads but also due to additional structural nonlinearities in conjunction with large amplitudes of structural deflections. In this regard, a supercomputer may again be a prerequisite for solving such problems.

(iii) Inclusion of active controls

Application of active controls for flutter suppression and structural load alleviation has received considerable attention over the last decade as aircraft designers seek methods to improve the performance and increase the structural life of new and existing aircraft[10]. The use of active control devices on aircraft offers potential benefits in the following areas which impact on structures and materials activities; load alleviation, flutter suppression, control configured aircraft and improved ride quality. Compared to classic linear aeroelastic analyses, aero-servoelastic investigations are much more complex due to the nonlinear dynamic behaviour of servohydraulic systems.

Thus, apart from structural nonlinearity (in the case of rotor blades) and aerodynamic nonlinearity (in the case of unsteady transonic airloads), a third type, i.e. control system nonlinearity, will be introduced in such aeroservoelastic analyses. Analytical solution of the overall aeroelastic problem for transonic flight with active controls, and possible inclusion in an interdisciplinary structural optimization process, is still prospective and appears nearly hopeless, even with the availability of a supercomputer! Nevertheless, a supercomputer would surely play a key role in futher exploration of the potential benefits of active control technology.

(b) Non-linear Structures and Materials Analysis

(i) Fracture mechanics

In the next five to ten years, the main efforts in this field will certainly be directed towards two kinds of problems; three-dimensional geometries and states of stress, and non-linear behaviour, at least in the vicinity of the crack tip. For a non-linear material it will be necessary to run the analysis for several interations in order to reach the "stabilised" state after stress redistribution due to the viscoplasticity (depending on the material this can require from three to one hundred iterations, the average being around ten), perform step by step time integration during each iteration, the numerical experience showing that about one hundred steps are necessary for convergence; and take into account a number of variables about five times greater than the corresponding elastic case.

Since on modern sequential computers a three-dimensional elastic analysis takes about five minutes of CPU time given the above-mentioned multiplying factors, the sustained rate of execution necessary to run the typical problem in one hour CPU time is approximately 400 Mflops. For the same problem, the storage requirements can be assessed at 5Mwords for the central random access memory and 200 Mwords of sequential access backing storage. These figures are obtained by considering the number of finite elements in the analysis, the number of Gaussian integration points by element, the number of matrices attached to each Gaussain point (stress, strain, displacement, plastic strain, plastic strain rate, size of elastic domain, internal stress, etc.), the size of the stiffness matrices to be factorized and the number of time integration steps per cycle.

(ii) Damage mechanics

It can be expected that the three-dimensional aspects will soon become a major preoccupation in the research domain. With the emergence of new materials such as composites (with metal or resin matrices), directionally solidified materials, single crystals, the problem will increase in size, due to the initial and strain-induced anisotropy of the material, and the anisotropy of damage, which means that this variable can no longer be considered as a scalar, but, at least as a second order tensor. Hence, by comparison with the Fracture Mechanics problem, we can expect a reduction in problem complexity, since no singularity is present, but an increase in size due to the anisotropic behaviour and damage description. In broad terms, computer requirements are similar to those of (i) above.

(iii) Post-buckling

At the present time, analysis in this area is generally done assuming elastic material behaviour. In the future, it can be expected that a more sophisticated description of material behaviour will be taken into account; for example, in the case of metallic materials, plasticity models have received considerable attention, and have been identified for various types of materials like stainless steels, refractory alloys for gas turbines, duraluminums, etc. For non-metallic materials, like carbon fiber-epoxy matrices, the dominant fact is the anisotropy which can be associated with a plastic behaviour of the matrix.

Given the fact that an analysis of post-buckling (typically including 100 degrees of freedom, 50 elements, with linear elastic behaviour) takes approximately 2 mins CPU time on a conventional mainframe computer, an estimation of the power required to run a problem of 5,000 degrees of freedom (large structure), in composite material with anisotropic non-linear behaviour (leading to a multiplying factor of about 100 in time as compared to an isotropic linear case), is about 200 Mflops sustained rate. Storage requirements, since the cyclic aspect in time is not present, are less important than in the fracture and damage mechanics problems discussed earlier and can be fixed at 2Mwords random access central memory and 5 Mwords sequential access backing storage.

2.2.5 General Remarks

An overall view emerges that computer users in structures and materials activities are broadly satisfied with conventional mainframe capability including Class 6 computers, but they require these facilities to be made more widely available, more interactive and more economic, with readily available software. There is little user demand yet for a supercomputer although there are problems for which such computers may, on present evidence, provide the only means of solution. These include interdisciplinary optimisation and non-linear materials analysis for which estimated performance requirements are 200 - 400 Mflops to complete in 1 CPU hour, 5 Mwords central RAM and 200 Mwords sequential access backing store. Although the structures and materials community are clearly not providing a driving need for a supercomputer today, there is a forseeable demand and if a supercomputer were to become available during 1985-90, with apposite software and at economic rates, then users would take time on it. Benefits will accrue by way of improved confidence in the realism of predictions. Apposite software would certainly include NASTRAN.

The time taken for demand to build up is likely to be quit significant. Research assessments will be a feature of early supercomputer activity. User community acceptance will require verification that the increased complexity of supercomputer solution methods provide a cost benefit through reduced qualification testing of the aerospace product. On a typical conventional main-frame installation, it is expected that structures and materials activities will account for about 10% - 20% of the total load. This is probably the upper limit for a national or NATO-wide supercomputer facility.

4269 Degrees of freedom

88 Optimization parameters

198 Opitmization constraints (Static and aeroelastic)

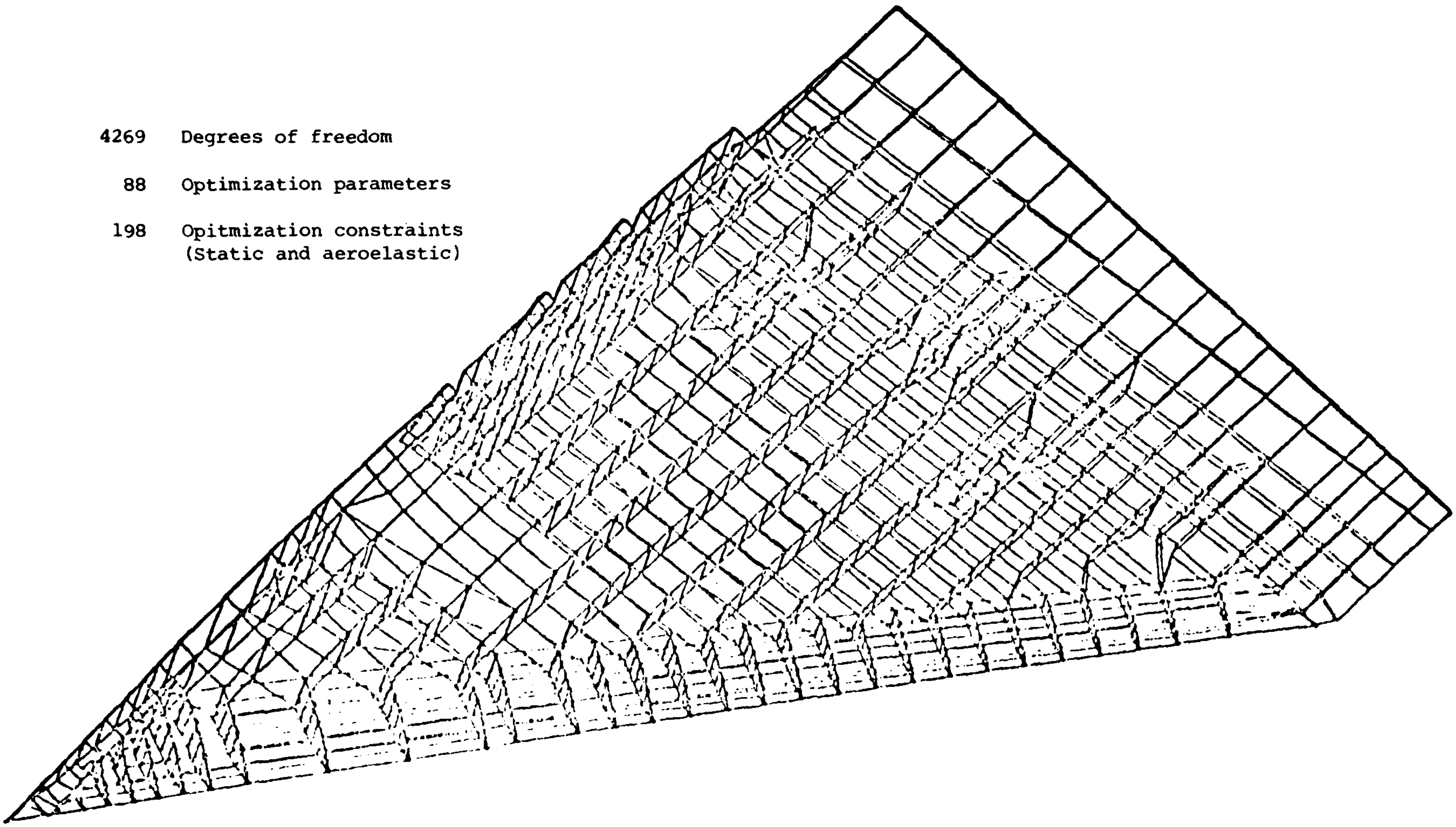

Figure 1 Finite Element approach to a delta wing [10].

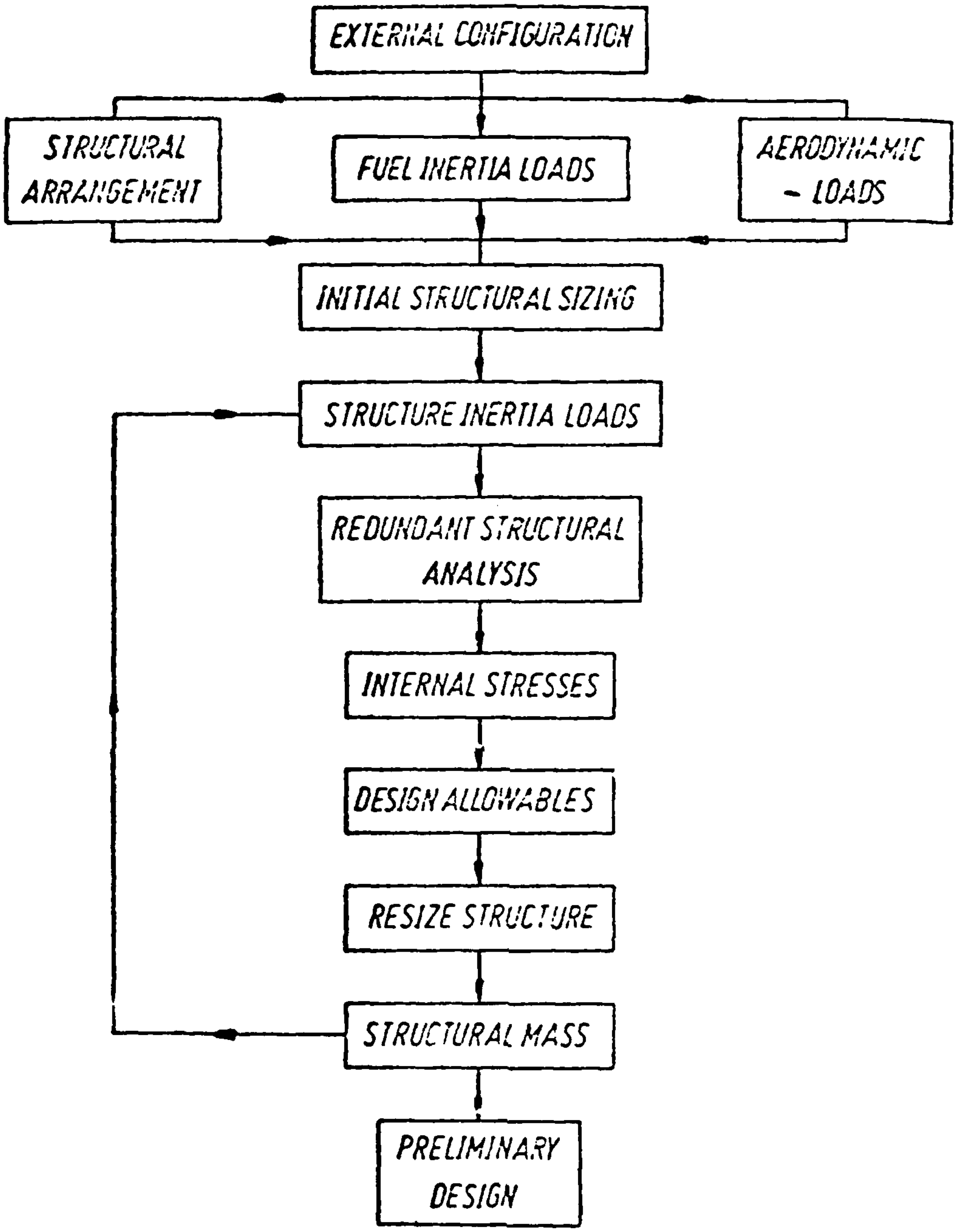

Figure 2 Aircraft structural design process

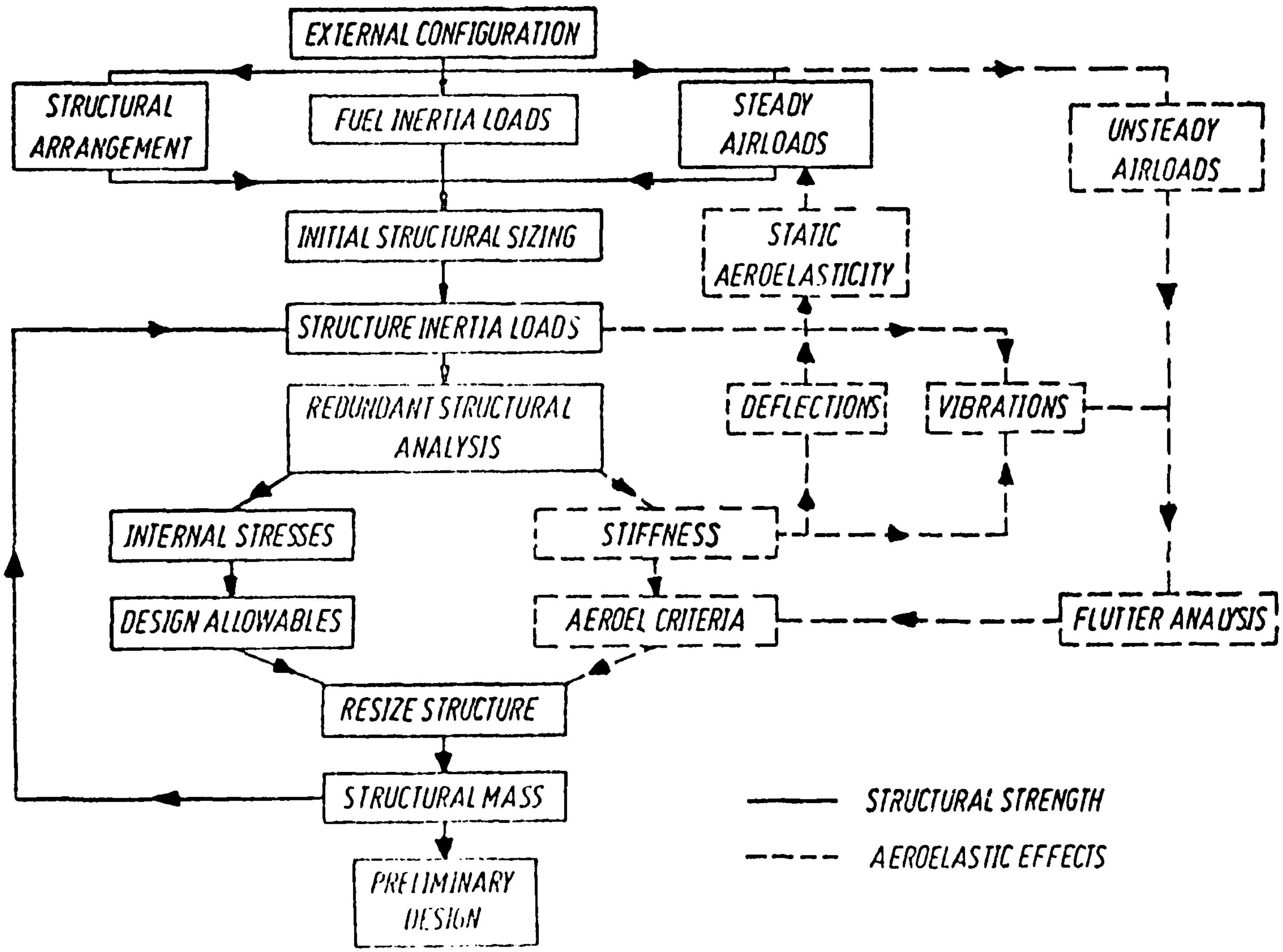

Figure 3 Structural optimization process including aeroelastic and dynamic effects.

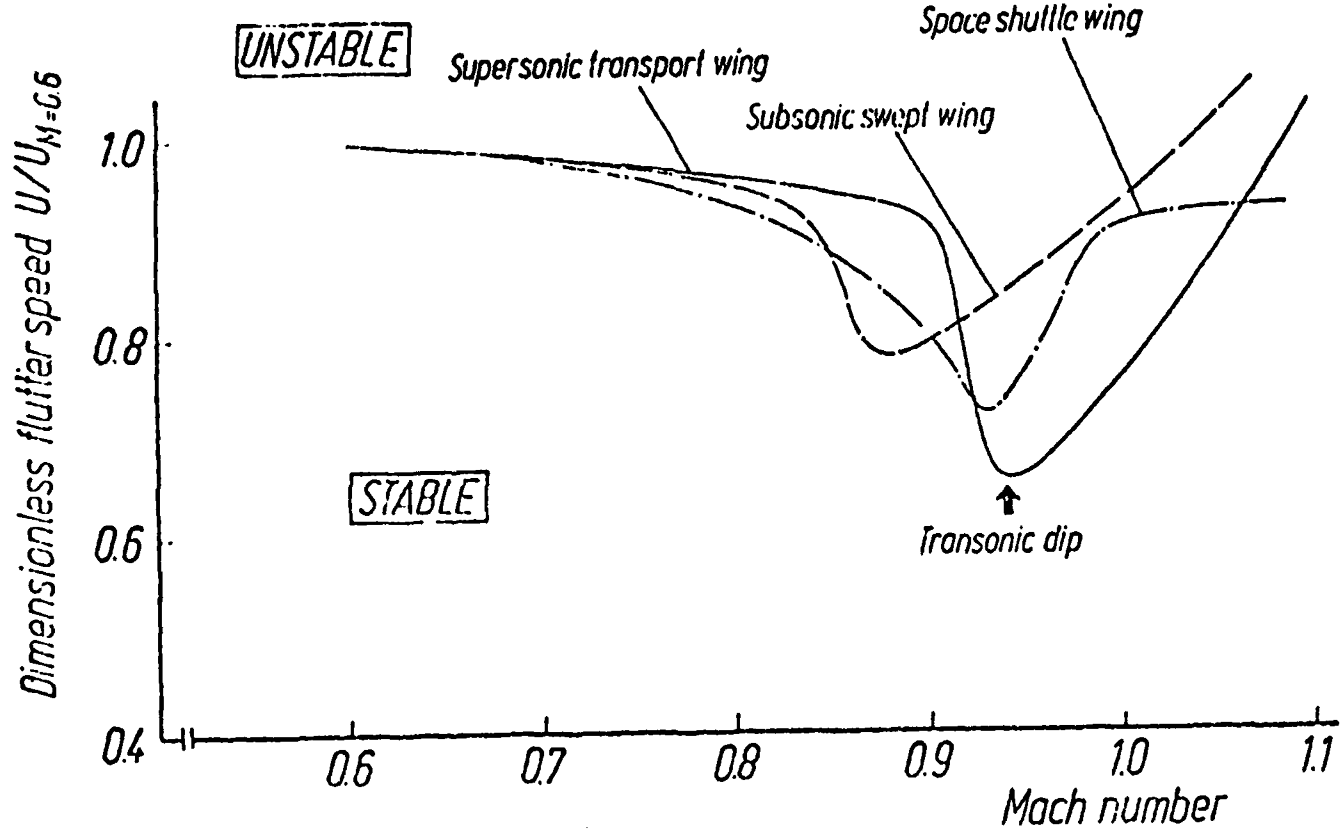

Figure 4 Flutter speed versus Mach number curve of several windtunnel-tested wing models, showing the "transonic dip." (Adapted from several NASA reports).

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A survey was conducted by questionnaire to provide information on the current status and need for advanced computers in structures and materials throughout the AGARD community.

Forty responses were received from eight countries; they are filed with R. Rollins, the Fluid Dynamics Panel Executive at AGARD H.Q. in Paris.

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2.3 Propulsion and Energetics

2.3.1 Introduction

In order to investigate the needs for advanced computational tools in the propulsion field, four main topics have been defined for discussion: Rocket technology; Internal Aerodynamics; Combustion, heat transfer, flames; and Engine structures (including vibration, flutter, structural integration, etc.)

Questionnaires were sent out asking for opinions on the present status of computer applications, as follows:

What specific items of basic research are restricted by the present state of computer facilities?

What specific items of design applications are restricted by the present state of computer facilities?

What specific computer enhancements, developments and improvements are requested to allow progress in basic research and in design applications?

Also, a questionnaire regarding computer facilities was sent to representatives of the AGARD Propulsion and Energetics Panel asking the following questions:

What are the existing large scale computing facilities (in the field of aeronautics) in your country?

What is their degree of accessibility to external users?

What large scale computing facilities are to be installed and/ or developed in the next years?

Is there a defined policy in your country with regard to the choice, in the future, between a computer network and/or centrally located supercomputers?

Many of the basic requirements in the four topics mentioned above are covered in the other Sections of the report and these will generally not be repeated here although they are fully valid for the applications in the propulsion field.

It can be stated that the needs for advanced computational tools in engine and rocket technology, above the basic needs of aerodynamics and structures, are determined by the complex interaction of the components occurring in engines. Examples are the flow configurations due to interactions betwen a rotor and a stator in a multistage engine configuration or the interaction between turbulence and chemical reaction kinetics in combustors. These topics are described in more detail below.

2.3.2 Research and Design Applications

(a) Rocket Technology

There are three basic areas of rocket technology currently being restricted by computer capability. They are: (a) modelling combustion instability, specifically including vortex shedding and turbulence in the models; (b) holographic diagnostics in determining particle size distribution in exhaust plumes; and (c) modelling real time kinetics from the flame front through the exhaust nozzle. The area of engine controls does not seem to be restricted by computer capability at this time.

Present day computers allow for single codes to optimize a rocket design and predict the specific performance, within a couple of percent, separately. A new large scale computer would allow combining these functions into a single code and allowing for real time kinetics which will permit performance predictions within a quarter of a percent. In the area of structural design of rockets, both for the case and the propellant grain, the limitation is not computer capability but determining realistic physical properties of the propellant and structural materials, and the true thermal and aerodynamic loads being applied to the motor.

(b) Internal Aerodynamics

The aim of the engine designer with respect to the aerodynamic performance of the engine components is to be able to estimate all the energy loss distributions and hence keep all loss sources to a minimum. This requires the ability to solve three-dimensional Navier-Stokes equations including the interaction between consecutive stages, the effect of the hub and shroud boundary layers and friction, the flow through the clearance and their interactions with the main flow. Since the flow is fully three-dimensional and since, even in the best case, the viscous regions within a blade row (with the exclusion of the first one) are not confined to the wall regions due to the influence of the upstream wakes and the relative motion between two consecutive blade rows, the whole flow field would have to be covered by a rather fine mesh in order to resolve fully the transport and the diffusion of the viscous regions.

An important topic in the estimation of the requirements placed on a computer system is the number of consecutive stages which have to be computed simultaneously due to their mutual interaction. Actually, for engines working in the high transonic range with choked stages, all stages would have to be taken up in the calculation since the mass flow will not be known in advance and since several stages can be in the choked regime simultaneously. Also, the prediction of stall and surge limits of stability also implies the need to calculate all stages simultaneously. Extrapolating one step further, one would ultimately wish to be able to perform a complete flow calculation of all the components: intake, compressor, combustion chamber up to the nozzle and the exhaust.

Other requirements are the calculations of some special aircraft flow fields such as thrust reverser operations and jet fountains in V/STOL aircraft near the ground; the three-dimensional heat transfer calculations in blade cooling design and also the complete acoustic fields that result from propulsion systems.

(c) Combustion Flows

The main restrictions to efficient combustor modelling can be summed up as follows:

(i) handling of turbulent three-dimensional elliptic flows with chemical reactions in combustors of realistic shape, where chemical reaction is described by a realistic multistep reaction system.

(ii) modelling of turbulence flames including the fluctuations of temperature and gas composition due to turbulent interactions of flow field and heat production from chemical reactions. However, presently the inadequate modelling of the physical phenomena hampers basic research in combustion more than computers do.

In the design field, large scale computers would bring progress, provided it is cost-efficient, in allowing the efficient modelling of turbulent three-dimensional elliptic flows without reactions as well as with reactions in combustors of realistic shape, e.g. annular combustors or reverse flow combustors with discrete hole air admission. Such computer programs could be used in the design of a combustor, namely for flow field studies, flow field optimization and/or parametric studies of particular influences (mass flow distribution, geometry etc..), before the usual perspex model (which is expensive and needs longer manufacturing times) is fabricated for a final test in a water rig. The same holds for the optimisation of the flow field with heat release in combustors before the final commitment to hardware development of a combustor is made. Whether these are realistic possibilities is determined by the cost of such computer exercises, as well as the availability of such programs and the ability to handle them.

It seems that other fields of design applications are less restricted by computer facilities than by lack of progress in setting up reliable design methods, e.g. for off-design calculation of combustors.

(d) Structures

Structural problems occuring in engines include vibrations, flutter, structural integration as well as typical non-linear behaviour of materials such as plastic flow, creep, buckling and all the problems connected to the analysis of non-isotropic materials in stress and vibration. These materials would include carbon/carbon composites and directionally solidified alloys.

2.3.3 General Remarks

The basic limits in further improvements in engine design are mainly connected to the limits of three-dimensional viscous calculations. This is the case for the internal flow problems and also for the combustion modelling.

Comparing the requirements for an engine internal flow prediction, and taking into account the basic unsteady character of the flow within the engine, one might consider that the levels of computer speed and storage, compared to those required by a complete aircraft at the same level of approximation of the flow description, would be one or two orders of magnitude higher than those determined by the aircraft design requirements.

It seems that, for the present and the near future the priority of the engine designers will be directed more towards the extension of the present capabilities toward more effective use of the available computer hardware and software. For instance, CAD/CAM is an area in which much work remains to be done. One need is to increase the data base capability for input, storage and retreival of complex geometry, engineering analyses and test results. Another is to achieve a three-dimensional description of all manufactured parts which would replace the drafting function and the use of drawings.

In the hardware area, comtemporary large computer installations are quite powerful in terms of speed of computation as well as memory. What is needed, however, is the diffusion throughout a design or research organization of computer facilities through remote access points. This is a question of economics which in turn may be a computer technological question. In addition, there is a need to realize quick turn-around on large scale problems.

2.4 Flight Mechanics

2.4.1 Introduction

The ever increasing use of large-scale computer systems has produced in recent years considerable advances in the field of aircraft and weapons system design and testing. With the expected further computer hardware and software developments, this trend will continue in the future and will result in significant increases in computational capabilities in various technical disciplines relevant to flight mechanics, to the related disciplines of guidance and control, avionics and to manufacturing techniques.

This Section presents the analysis and conclusions reached by the representatives of the Flight Mechanics Panel in regard to the current status of, and need for, advanced computational capabilities in simulation and flight testing. The conclusions result, in part, from questions prepared in each of the subject areas and circulated in Europe and in the US. The responses (see Appendix 2.4.1 for the participating organizations) constitute a good basis for the analysis of the computer's role in flight mechanics. Results of discussions of the Working Group and additional comments are also included.

2.4.2. Current Status and Future Needs in Simulation

Currently flight simulation is meeting escalating challenges imposed by the aviation community. Advancing computer technology has been a key factor in spearheading the expanding role and acceptance of flight simulators in aeronautical research, development, and crew training.

The advantages of simulators over airborne flight operations include reduced cost, fuel savings, safety, and more efficient training[1]. Research and development areas where simulators play a vital role include: investigation of the handling characteristics of new aircraft; practice of emergency procedures and maneuvers which can be hazardous if conducted in the air; evaluation of new display and control systems, pilot capabilities and workload, crew roles and flight procedures for possible reconfigurations of the air traffic system; and weapons system development.

Research flight simulators, used in coordinated programs with wind tunnels and flight testing, add another dimension to cost effective development of new aeronautical and space systems. The U.S. National Aeronautics and Space Administration (NASA) commitment to comprehensive use of flight simulators in support of its ongoing programs is well known[2]. NASA also maintains a Simulation Technology Program with emphasis on long-term basic and applied research of flight simulator components and systems, along both disciplinary and interdisciplinary lines[3].

Military uses of simulators for aircrew training, particularly undergraduate pilot training, are legendary. One UH-1 (Huey) flight simulator used sixteen hours a day, five days a week is estimated to save approximately $3.5 million/year, and one AH-1 (Cobra) simulator, for the same utilization, will save $ 6.8 million/year as compared with using the aircraft[4]. The cost saving resulting from reduced demand on aircraft are clear. But what have simulators done with combat readiness? Future conflicts will no doubt involve higher speed, real-time decision making, based on more information, and will require more team work than ever before in history. Projected near-future developments in computer technology are providing military planners with new options for simulator devices that have the ability to recreate, at reasonable cost, the level of quick and complex decision making that is necessary for, say, force-on-force air combat environments. Such conditions may be too dangerous or expensive to create in real life and possibly the desired training could not be accomplished without simulation, or if training were attempted, done only crudely with actual equipment. Force-on-force simulation concepts, with real-time command and control would offer the prospect of honing the proficiency of the team.

It should be noted that the civil sector has realized savings through use of simulators similar to those of the military sector. One U.S. airline, for example, estimates that it costs $3,000 more per hour to train an L-1011 pilot in the plane than in the simulator and suggests a total saving of $42,000 on each pilot who undergoes extensive simulator training[4]. It is clearly more difficult to prove the case for lives not lost and injuries not suffered.

But what about proficiency which, in the final analysis, is the ultimate judge of simulation effectiveness? The U.S. Federal Aviation Administration (FAA) has recently issued a rule (FAR 121, Appendix H) which allows expanded simulator training, checking and certification of flight crews[5]. The Phase III simulator requirement set by the FAA would allow 100% line-oriented-flight-training (LOFT). That is, a pilot could graduate from one type of aircraft to another with total training on the simulator and the FAA estimates, when fully implemented, that the new rule will permit saving of 73,000,000 gallons of fuel per year. In order to satisfy the FAA requirements, simulator computers must be 32 bit machines with high order language programs and provide extensive software diagnostics and self-test capabilities.

Digital computer technology permeates every aspect of modern flight simulator design, development and operation. However, development of engineering and perceptual requirements for man-in-the-loop- simulation is a complex task involving numerous trade-offs between simulation fidelity and costs[6,7,8]. In specifying the cue environment and attendant computational requirements, the designer must establish the need for particular cues as well as the requisite fidelity of presentation. The choices made are highly important because the validity and utility of the simulation results can be critically dependent upon them and because the decisions involve major costs in the simulation system. Unfortunately, the decisions are quite difficult to make objectively, inasmuch as the choices depend on complex psychological as well as engineering factors and the intended purpose of the simulator, i.e., training simulators often have different needs than research simulators.

A consistent methodology for design of simulator-based man-machine systems remains poorly defined. "Rule of thumb" and "Ad hoc expert" judgment regarding open loop response of computational and cueing subsystems and subjective feedback from pilots are all helpful in developing the engineering and perceptual requirements for simulators, but lack the specificity inherent to a "science of simulation." An approach to this problem, researched by NASA over a period of years, has been to exploit and extend opportunities afforded by developments in man-machine systems theory whereby simulator characteristics and human limitations can be assessed in terms of overall closed loop system performance[9,10,11]. Consideration of vehicle dynamics, simulator computational and hardware characteristics, mission criteria and human capabilities within a single analytical framework provides a key milestone toward a science of simulation.

An assessment of current and likely future trends in computational capability required to support real-time simulation of air-vehicle systems reverts to analysis of four key technical issues:

How much computational fidelity is 'enough'?

Can 'enough' be quantified with precision, in terms of a preferred computational architecture?

If we know quantitatively what we want, can the architecture be achieved and at what cost?

If achieved, what assertions can be made regarding validity of the approach?

Clearly, the above questions can be discussed only in terms of the precise aviation context in which they are asked, i.e., there is little likelihood of a universal simulator uniformly valid for all purposes.

The following paragraphs provide a review of: the evolution of digital flight simulators; the role of computers in real-time flight simulation; and advanced computational capabilities in flight simulation and visual image generation. A questionnaire on computer requirements in simulation was used to solicit the view of industry and government laboratories in Europe and the US.

(a) The Evolution of Digital Flight Simulators:

The first known discussion of the computer method of flight simulation is that of Roeder in his German Patent Specifications[12]. During the period of World-War II rudimentary characteristics of aircraft flight and engines were mechanized in real-time on both pneumatic and mechanical computers. Two of the best known synthetic trainers using these techniques were the Link and Silloth devices[13]. A major advance in simulation during the war period was in the development and use of the electronic analog computer (differential analyzer) to solve the equations of motion of an aircraft, thus enabling simulation of the vehicle response to aerodynamic forces as opposed to an empirical duplication of their effects. The earliest widespread application of analog computers was in the area of flight simulation. By the late 1940's, electronic differential analyzers were the only type of computer able to solve a reasonably complete set of flight equations in real-time.

It is interesting to note that analog computers and hybrid derivatives (combined analog-digital systems) are still in use today.

During the period when analog computer technology was at its zenith, aircraft manufacturers had limited analytical information on the airframe performance, stability and control and engine characteristics, thus making analog techniques plausible. The advent of the large subsonic jet transport changed the picture drastically as aircraft manufacturers began to produce more complete data sets, over expanded operational envelopes, and conducted more extensive flight development programs. Together with requirements for driving motion and visual systems then being introduced and pressures from the simulation research community and training device operators to improve accuracy, significant increases in the amount of analog computer hardware became necessary to support the simulation function. At this point, the law of diminishing return began to operate and the cumulative errors and reduced reliability caused by the additional hardware negated the expected improvements which should have resulted from simulation of the more extensive aircraft data sets. It thus became obvious that the demands for increased fidelity of simulation and reliability could no longer easily be met with analog techniques even with the use of solid state elements which appeared in the 1960s.

It was indeed fortunate that the second generation of digital computers emerging in the 1960s were able to satisfy many of the speed and cost requirements posed by real-time flight simulation. As a consequence, there was an impressive swing to digital simulation for all but the most demanding application requiring wide operational bandwidth. It was realised from the earliest days of programmable electronic digital computers that real-time digital simulation would be a potential application. The advantages of digital computers include improved flexibility, repeatability, dynamic range, and configuration control standards. By the late 1960s general purpose digital computers were found to be suitable for simulation, with its large input-output requirement and high-speed arithmetic capability, and the use of special purpose machines declined. Today special purpose digital computers are only used in applications demanding very high speed processing, such as missile and rotary-wing configurations, radar simulation (weather and land mass) and computer generated imagery.

(b) The Role of Computers in Real-time Flight Simulation

Flight simulation is achieved by mathematical modeling of a vehicle's aerodynamics, control system, propulsion, structure, avionics, and environmental characteristics and by using computer controlled displays, motion and control feel systems to give the pilot the illusion of actual flight[14,15] (fig.1). Mathematical models used to simulate modern aircraft consists of an extensive set of nonlinear differential equations, with arbitrary discrete and continuous forcing functions, large amount of aerodynamic function data depending on 4 or 5 variables, and a multiplicity of algebraic constraints imposed on the system states. The generic character of the mathematical problem statement is shown in figure 2.

Computer solution of the implied initial value problem allows simulation of the complete range of static and dynamic aircraft operating conditions, including landing and takeoff, combat and tactical maneuvers, emergency situations such as icing, engine failure, stalls, and component malfunction. Other significant parts of the computational problem involve fuel system equations, weight and balance changes, autopilot functions, navigation functions and radio aids, air data and radar equipment. To maintain realism the operation of the aircraft's hydraulic, pneumatic, electrical and mechanical systems must be faithfully reproduced as well as proper dynamic and static response of the cockpit instruments. Often in research simulator applications many of these latter systems are not explicitly simulated. Because of the presence of the pilot-in-the-loop, or hardware and avionics in the loop, the complete set of equations must be solved in real-time; that is, the simulated events must occur in the same time scale that they would occur in the actual aircraft. For sufficiently complex aircraft systems and associated math models, the real-time constraint can place severe demands on available computer assets. The real-time constraint for a serial processor, with analog input-output, can be expressed as

$$|\text{Code Processing Time} + \text{Input/Output Time}| < |\text{Sample Period}| \qquad (1)$$

Computationally, the typical flight simulator can be broken down into the following basic operations:

Function generation (up to 5 independent variables)

Numerical integration

Coordinate transformation

Addition and subtraction

Multiplication and division

Analog and discrete input/output

Bulk data access (Nav. data bases)

Decisions and branching (Boolean)

For a particular application, the real-time constraint as given by (1), and the total number and mix of operations, will determine the required simulation computing power. Many operations such as integration, function generation and coordinate transformations, are performed on a digital computer by approximate numerical techniques requiring many computing steps or iterations. In real-time aircraft simulation, the computer must carry out all calculations called for in the mathematical model, including input/output, a sufficient number of times per second to achieve dynamic fidelity of the highest natural frequency present in the solution response. Generally, this demands a solution rate at least 10 x Nyquist Rate of the aircraft's highest frequency i.e. 20 samples/cycle. Using this criteria, the required computational duty cycle (sample period) as a function of aircraft natural frequency is shown in fig. 3.

Closed loop natural frequencies of man/machine systems encountered in aircraft and space vehicle simulation are typically less than 3 Hertz. Moreover, the required solution rate also is strongly dependent on the discretization technique used for the use for integration[16]. Although closed loop bandwidth of simulators may be relatively low, particular subsystems can have large and widely separated eigenvalues as represented in fig. 4. Thus, in selecting a sample rate for real-time simulation, careful consideration must be given to method of discretization, system eigenvalue distribution and minimum acceptable end-to-end phase shift.

Taking all the above factors into consideration, a measure of required simulation computer power, for a given application, can be expressed as:

$$[\text{Required Simulation Power}] \; \alpha \; [\text{Problem Complexity}] \times [\text{System Bandwidth}] \qquad (2)$$

Using (1) and (2) and a selection criteria for sample rate, various computers can be compared as regards their potential for flight simulation application and predictions of computer power required for new applications can be made.

Equation (2) can be expressed more precisely as

$$DFLOPS = N_O P_S S_C F \qquad (3)$$

where DFLOPS = Dynamic Equivalent Digital Operations Per Second

N_O = normalized static operations to update dynamics per program pass
P_S = number of program passes per sample of input data
S_C = number of samples per cycle of largest operational frequency of interest
F = operational frequency (bandwidth) in herts

DFLOPS is a measure of required simulation computer power for a given application. The parameter N_O is determined by the nature and mix of mathematical functions as discussed previously and is greatly influence by the aerodynamic data base used to describe the simulated vehicle. P_S is determined by the discretization method used to integrate the vehicle dynamics i.e. $P_S = 4$ for 4pt. Runge Kutta methods requiring 4 derivative evaluations and $P_S = 1$ for Adams multi-step predictors. As discussed earlier, $S_C = 20$ samples per cycle will insure a reasonable computational fidelity of the highest natural frequency present in the solution response. For example, the full envelope simulation of a large conventional transport aircraft requires $N_O = 4 \times 10^4$ operations (non-aeroelastic). Choosing $P_S = 4$, $S_C = 20$ and the dynamic bandwidth parameter $F = 1.5$

Hertz results in a computation requirement of 4.8Mflops (Million floating point operations per sec.).

(c)Advanced Flight Simulation and Visual Image Generation

In order to obtain quantitative data and narrative input, a survey was conducted in Europe and the USA regarding the current status of, and likely future trends for the computational aspects of real-time simulation and related visual image processing technology. The survey approach was used so as to gain maximum information in minimum time, with as broad a representation as possible. In addition to the AGARD survey, other pertinent information was acquired from one-on-one contacts and results from a similar survey recently conducted by AIAA regarding engineering simulation facility trends. With the approach taken, a representative cross-section of opinion, interests, concerns, and supporting data have been compiled.

A questionnaire was established (see Appendix 2.4.2) and circulated on both side of the Atlantic. In Europe, representatives of the AGARD Flight Mechanics Panel were solicited to distribute the questionnaires to various organizations in their own countries. In the U.S. 32 organizations were sent questionnaires and 19 responded.

Based on the quantitative data and narrative explanations solicited in the survey the following summary is possible:

1. All types of simulators included in the questionnaires are currently operated. There was a decided propensity toward military applications, with approximately 30% of the responses oriented toward civil applications. Of the reported simulators, air combat devices appear to be the most complex and perhaps most costly, with the single exception being the U.S. Space Shuttle Mission simulator. A majority of the responses indicated use of simulators for general research including aircraft design and development as opposed to crew training, although in some cases a precise line between the two is hard to draw. Needless to say, all respondents implied that simulators, in one way or another, are used as part of a learning experience. Two of the 33 responding organizations indicated that they operated inflight simulators. The above data are summarized in figure 5.

2. Current in-place computational capability includes minicomputers, midicomputers and to a much lesser extent, highly integrated and centralized large main-frame configurations (see figure 5). Approximately 50% of the responses indicated laboratory configurations containing mini-computers in some type of loosely-coupled network. For purposes of establishing a frame of reference, some definitions are in order:

   mini-computer - general category of VAX-11-780, SEL-32-77

   midi computer - general category of UNIVAC-1100/44

   large main-frame - general category of CDC-7600, CDC CYBER-175

3. All the above types of computers are currently used in support of real-time simulation. A significant number of hybrid systems were reported to be in current use. The European community reported several configurations using array-processors interfaced with minicomputers. The general response given for use of hybrid computation and systems including array-processors is the desire to increase operational bandwidth in applications such as rotorcraft and radar simulation. One organization which employs an array-processor in a high-speed graphics application expressed concerns about the complexity and cost of software development. Based on all 33 responses, current in-place computational power ranges between .2 Mflops and 10 Mflops depending on the particular facility surveyed. Most of the respondents indicated that with the computers currently available in their respective labs, fairly complex mathematical models of the air-vehicle system are used, including nonlinear aerodynamics, propulsion, structures, flight controls, navigation and weapons systems, displays and environmental simulation.

4. Rotorcraft simulation appears critical from the computer viewpoint. The rotating blades are relatively flexible, and the rotor aerodynamic forces and moments depend on a radial coordinate from the hub and on blade asimuth.. Sections of the blades can experience nonlinear

aerodynamics conditions such as stall or high Mach number flow for particular flight conditions and additional dynamic complexities occur due to rotor - fuselage flow interference. All respondents actively engaged in rotorcraft simulation indicated that comprehensive models exist which attempts to incorporate the above features, however, large high speed computational capacity is required and the programs run much slower than real-time. At least the equivalent power of 10 Xerox Sigma-8 computers are required for advanced rotorcraft simulation[17]. In the final analysis the answer to the question of how complex must the model be depends on the intended simulator application.

5. Additional areas where respondents indicated that current computer systems limited simulator performance were:

   - Multi-Aircraft Gaming Environments + Weapons Systems With Command and Control Interfaces

   - Full Envelope CCV With Simulated Avionics

   - Iron-Bird RPV Simulation

   - Simulation Of Remote Manipulator Systems For Space Application

6. In the case of multi-aircraft gaming simulation the basic problem appears to be one of available computer capacity at acceptable cost (number of computers) rather than computational speed. On the other hand, the remaining areas were reported to involve dynamic distortions related to computational bandwidth and attendant computer latencies, indicating the need for higher speed machines using current math models. A summary comparison of simulation model complexity for several aircraft types is shown in figure 6.

7. The vast majority of responses to the subject survey indicated plans to upgrade current simulation computer systems. There was a strong propensity toward distributive networks and use of new generation 32 bit computers. The current generation of 32 bit minicomputers provides the flexibility, both in hardware and software, which is now felt to be essential in modern simulation complex, and at a reasonable cost.

8. Approximately half the responses indicated plans to improve performance of analog I/0 and D/D interfaces. Developments in electronics component technology, as well as influencing the price to performance ratio of minicomputers have had their impact on simulator electronics in general. The analog-digital linkage, the interface between the computer complex and the simulator, instruments, controls and other analog devices, vividly demonstrate this improvement. Currently produced linkage systems make wide use of integrated circuit analog to digital converters, digital to analog converters and analog multiplexers to increase reliability and simplify maintenance. Those organizations whose work heavily involved avionics systems indicated plans to improve D/D interfaces using currently available data-bus technology.

9. Some respondents indicated that upgrade plans of current systems were motivated by the desire to improve model fidelity through increased computing bandwidth for advanced applications. In this regard, there was general agreement that μ-processor and LSI technology will have growing influence on the way real-time simulation dynamics are performed. The prospect of a 32 bit μ-computer with 1m bit memory on a single silicon chip by the mid-1980s is keenly anticipated by the simulation community. The opportunities afforded by these developments are expected to result in tightly coupled concurrent distributed networks uniquely configured for the real-time simulation application[18]. Although hardware costs may be drastically reduced, many express concerns regarding software cost and risks, for such architectures. Trends have already developed toward the use of independent computers for digital simulation of high bandwidth subsystems such as control loading and motion system control, previously the domain of purely analog computers.

10. A summary of survey data regarding plans to upgrade current systems is presented in figure 7. Most respondents agreed that future simulation computing needs would likely be satisfied by natural computer technology development and there was a consensus that general purpose computers (standard product) are preferred over special purpose devices.

11. Other than rotorcraft, the evidence collected during this study suggests that computational dynamics are satisfactory, there is no need to develop specialised computers or software techniques and progressive improvements will be acceptable. This was a difficult area to judge

because of the subjective nature of the responses and the lack of a standard basis for comparison. Typically, for fixed wing aircraft simulation, computational intervals were reported to range between .1 sec and .025 sec. (sample rates between 10 Hertz and 40 Hertz).

As discussed earlier, rotorcraft simulation appears to be critical from a computer viewpoint. The computational fidelity of a rotating blade element model depends on the maximum allowable blade azimuth advance in one real-time computer cycle i.e. $\delta\psi = \Omega h$ (where Ω is the rotor speed and h is the computational interval) and the number of radial blade segments b, required to faithfully represent aerodynamic force and moment distributions [19]. Problems have arisen in the past when using the rotating blade element model for man-in-the-loop real-time simulation applications primarily because of inadequate computing bandwidth of current computers. In order to use this model at all, gross degradation of the rotor representation and/or integration interval size were required. This was done so that the computer execution time for the active part of the program would be less than or equal to the desired integration interval; in other words, it would achieve real-time execution.

Figure 8 shows the effect of rotor rotational speed and azimuthal update on allowable program execution time in order to prevent computational divergence of the flapping equation of motion. This is represented by the relationship, $\delta\psi = 57.3\Omega h$. Several present and future helicopters are provided for comparison. As seen, the maximum program execution time available for the RSRA vehicle, if given a 30° azimuthal advance, is approximately 25 milliseconds. This program execution time must now be matched to the computational speed of the digital computer which is used for the simulation study.

Figure 9 represents the computational situation for a rotorcraft vehicle with a five-bladed rotor model and a rotational rate of 200 rpm. An azimuthal advance angle of 30° was chosen for illustrative purposes. Program execution time has been normalized to unity for the CDC 6600 computer. The CDC CYBER 175 with the NOS FTN compiler (optimization enabled) is represented at its tested bandwidth of 3.5 times faster than the CDC 6600. Minimum blade and blade-segment boundaries are presented. The cross-hatched area represents the combinations of blades and blade segments which can be modeled on the CDC 6600. Note that the five-blade five-blade-segment representation normally used (5b x 5s) is on the borderline of achieving real time for this azimuthal advance angle and leaves no execution time for additions to the program. It can be seen that the CDC CYBER 175 would be able to handle the representation easily. Note that for a given computer, and fixed $\delta\psi$, the demand on central processor assets depends linearly on the number of blades simulated and the number of blade segments .

Conclusions drawn from the above lines of reasoning are largely determined from steady-state analysis. The required computational interval h is not uniquely determined without consideration of rotor dynamics. Dynamic computational fidelity depends on factors involving numerical stability and related questions regarding the particular method employed for rotor discretization. The maximum eigenvalue encountered in the rotor computations (flap/lag) is approximately

$$\lambda \simeq \Omega j$$

however, from a numerical viewpoint the computational bandwidth must accommodate the range $0 < \omega < N\Omega$, where N= number of blades. Using the selection criteria discussed previously, the rotor computational duty cycle is chosen to achieve 20 samples/cycle i.e.,achieve

$$h = \frac{\pi}{10N\Omega}$$

where Ω is given in rad/sec.

Figure 10 shows the allowable duty cycle or a function of Ω for N=3 and N=5. Comparison of figures 10 and 3 clearly demonstrate the severity of the rotor-craft simulation problem. For Ω = 21.29 rad/sec. (200RPM) and N=5 the required computational interval is estimated to be h $\simeq$ 3 msec., and the resultant azimuth advance angle is $\delta\psi \simeq 3°$, which is a factor of 10 smaller than estimated from steady state analysis. Figures 11 and 12 show the effect of increasing computational interval from 4msec. to 50msec. on vehicle dynamic response at 120 knots for a five blade - five segment rotor. The dynamic distortion is obvious and one can see that the numerical solution and aerodynamic definition of the total model have broken down at the larger computational interval. Both the vehicle and rotor are highly unstable. The dynamic responses were obtained by starting with the vehicle in trim conditions and applying a 5 percent 1-second lateralcyclic pulse. Considering the rotorcraft model used and the known performance of the CDC CYBER -175 operating in real-time, it is estimated that the equivalent power of three 175's would be needed to satisfy the h $\simeq$ 3 msec. goal.

Computer generated imagery (CGI) is an area of rapid growth and development stimulated by the increasing demands for computer-based visual simulation[20,21]. Advancing computer technology has been a key factor in CGI development and in the acceptance of computer based visual simulation systems for aeronautical research, development, and crew training.

The importance and usefulness of out-the-window visual simulation can be judged best by the recent large increase in the use of this equipment in air-carrier training simulators and the expanding role of simulators in the military arena. It is important to note that out-the-window visual systems are often the most costly item in acquisition of new simulator devices. Because of the significance of rich visual perceptual field in aviation systems operations and the attendant high cost of visual simulation, researchers must make trades between the need for particular cues as well as the requisite fidelity of presentation. Research to establish psychological as well as engineering requirements for low cost, broadly applicable out-the-window visual simulation is dominated by challenges which result from the extremely high performance capabilities of the human eye. Much research is needed to identify minimum essential visual cues for particular flying tasks and relating those cues to the performance and computational specifications of the visual simulation devices.

Results of the subject survey indicated the three principle types of visual systems in current operation: camera-modelboards (TV), CGI and shadowgraph devices. The use and acquisition of camera-modelboard systems appears to have peaked and are now experiencing rapid decline. There is a definite tendency toward CGI based on an architecture of microprocessors interfaced with mini-computers[22]. The survey revealed a uniform opinion that significant advances in computer generated imagery are needed. This is an area where computer technology development can provide the maximum benefit in both civil and military simulation applications.

Most CGI systems model the playing area using polyhedral models with straight edges and plane faces. One of the big steps to be taken in the next generation of CGI systems is to remove this dependence on polyhedral structures to approximate the curved surfaces simulated. This will reduce the computer storage requirements since curved surfaces are defined by fewer curved patches than planar ones for a given accuracy of fit. However, the realization of systems with the equivalence of several hundred thousand or more edges coupled to display devices of 180° H x 70° V field of view with 1 arc minute resolution will require significant technology advances in architectures and related mathematical software. CGI computer systems will remain highly specialized and such configurations will not be useful for general scientific applications. General purpose computers are not expected to be economically acceptable in a CGI support role. The prospects of achieving high fidelity visual simulation based on CGI techniques at acceptable cost, are extremely promising. The future of CGI lies with VLSI technology and developments in high density optical disks to replace magnetic disks [23]. The equivalent computing power of future systems will be massive, however, they will remain highly specialized devices.

2.4.3 Current Status and Future Needs in Flight Testing

The main objectives of the section are to: review the flight testing data acquisition and recording equipment currently in use; identify the data processing systems; discuss their usefulness and limitations concerning hardware and software; and indicate their likely upgrading for future needs in consonance with the latest technological advances. The questions and responses to the questionnaire on the use of computers in flight testing are given in Appendix 2.4.3.

(a) Current Flight Measurement and Data-processing Systems

Flight testing of aircraft and missiles is a complex process requiring careful planning and preparation, execution, documentation and interpretation. Test programmes are planned and carried out following various test objectives: developmental testing (performance, flying and handling qualities, system and subsystem functional testing, etc...); qualification test and evaluation of the developed product; operational tests, evaluation and/or certification. They involve personnel belonging to manufacturers, to the government or the users themselves.

To complete these comprehensive test programmes in the best possible conditions and within the generally tight time and cost schedules, a highly automated and computerized measurement and data processing system is now an absolute prerequisite. It is important to point out, moreover, that manufacturers and flight test centers frequently conduct several flight test programmes in the same time period with several aircraft models flying simultaneously. Hence, the structure of the testing organization and the operating system must be conceived to perform efficiently in this multi-aircraft testing environment.

In addition to basic data processing, computers are also used at various other levels in the flight testing process. Therefore, to highlight their exact role in the whole process, a short description of the complete measurement and data processing system appears appropriate.

Modern data acquisition and data processing systems comprise (i) real-time and quick-look capability, (ii) data acquisition and recording equipment, (iii) ground-based measuring equipment, (iv) airborne processing and/or ground processing of telemetered data, and (v) data processing.

(i) Real-time and quick-look capability

A common feature of these systems is their capability to process and display the most important part of the measured data on-line in real-time (or near real-time when the processing implies higher level analysis, as for example in flutter testing). This highly desirable "real-time" and "quick-look" capability is extremely useful: it improves the flight safety by allowing better flight program monitoring; improves the data quality by accurate control of the test program execution and by an immediate "repeat" of an inaccurately performed test exercise; it allows the test conductor and the instrumentation engineer to monitor continuously the functional integrity of the instrumentation, validate the acquired test results or in case of partial instrumentation failure decide on the continuation or the termination of the flight; equipment malfunctions or failures can be analyzed during the flight and the necessary actions initiated, even before the landing of the test vehicle; the cost-effectiveness of the testing is significantly improved by the reduction of the number of flight hours and of the time required to process the data and thus the additional expenses for hardware and software are largely recovered, and the immediate visibility of the results creates a more effective integration between the flight test personnel and the various involved specialist teams and allows a reduction of the turnaround time between flights. This last point is particularly important, when considering the steadily increasing quantity and complexity of flight programs and the tight time schedules available for their completion.

It must be noted that real-time data processing must be supplemented by comprehensive batch processing, which remains as important as in the past for more elaborate and higher level analysis (as for example for performance analysis, parameter identification, load substantiation, inlet dynamics, weapon system evaluation, etc...). In view of the huge quantity of data to be analyzed, batch processing must be also highly automated and it is in this area that large computers will play an increasingly important role.

Finally, it is also important to mention that a real-time data system cannot be exploited to its maximum capability without thorough and coordinated test planning with the participation of the specialists of all the involved technical disciplines. In particular, in contrast to earlier systems where instrumentation and computer engineers were able to work more or less independently, integration and operation of a real-time system implies close cooperation, from the early stages of the project, between the flight test, instrumentation and computer engineers. It is at this stage that flight objectives must be clearly formulated, instrumentation accuracies defined, and computation algorithms and the corresponding software requirements specified.

(ii) Data acquisition and recording equipment

On-board measuring equipment consists of: sensors, transducers, signal conditioners (amplifiers, attenuators, gain rangers, ...), filters, analog and/or digital encoders (modulators, multiplexers), analog to digital converters (when applicable), interfaces and controllers, data buses and storage devices, timing devices, and calibration signal generators. According to the aircraft size and complexity, the required measurement accuracy and the budgetary situation of the particular flight test program, the solutions may vary from simple, cheap and limited accuracy equipment to sophisticated very sensitive instrumentation.

The output of the data acquisition system can be recorded on various types of recorders (photorecorders, trace recorders, etc...) but the basic recording instrument is now the magnetic tape recorder due to the numerous inherent advantages of the magnetic recording, in particular in relation with the computerised data reduction procedure. Magnetic recording in flight testing is generally made using multi-track open-reel tape recorders (usually 14 tracks, sometimes 28 or 42), but also with other support formats as cassette or cartridge (in particular when compactness is an important requirement). Recording modes currently used are the analog frequency modulation (FM) and the digital pulse code modulation (PCM), although in the past many other types of modulation were practiced.*

To record the large number of parameters (several thousands in some flight test programs) on a limited number of recorders, if possible on a single recorder, both FM and PCM use multiplexed recording modes where the signals are mixed: i.e. frequency division multiplexing in FM, where data signals modulated with various carrier frequencies are mixed on one track; and time division multiplexing for PCM, where a number of digitized data sources are sampled in a prescribed order and the resulting digital words recorded sequentially on one channel of the tape (if necessary on several tracks).

Due to the higher accuracy of digital recording (by about 20 dB) there is a definite trend to the use of PCM in recording higher and higher frequency bandwidth phenomena. Until now PCM performance was limited by the capabilities of the available current technology hardware , e.g. analog to digital converters and associated equipment, high density magnetic tapes compatible with the high bit rates, etc,. However, recent progress in these areas and the inevitable advances in miniaturization are rapidly improving the situation and it is felt that high frequency PCM recording will be practicable in the near future at acceptable weight, volume and cost. Alternate solutions to overcome these limitations can also to provided, as for example by the use of static memories.

For certain types of measurements or for qualitative surveys the airborne magnetic tape recording is frequently supplemented by airborne cameras, video cameras and video recorders. Video-camera outputs can also be telemetered and received at the ground station.

(iii) Ground-based measuring equipment.

When the flight test program requires the knowledge of the aircraft, missile or other weapon trajectories and/or attitudes, as in takeoff and landing measurements, in spin testing, in noise measurement, in weapon release trials, etc...tracking of the vehicles or weapons is carried out by such ground instrumentation as cinetheodolites, radars, laser ranger/trackers and sometimes by high speed cameras. Accuracy of the cinetheodolites and laser/trackers are comparable and are generally acceptable for the previous types of tests, but the radars are only marginal, at least in certain flight conditions.

In the past, operating and processing of cinetheodolite data was manual and very tedious. With negligible aiming errors real-time processing can be made by a dedicated mini-computer receiving the digitized telescope positions of the theodolites. If however the aiming errors need to be compensated for to improve accuracy, a useful expedient is to apply smoothing during processing. For even higher accuracy manual treatment of the film is needed.

An alternative, method of tracking the aircraft is by a servo-controlled system, with possibly an active transponder, which automatically follows the target. Aiming errors are reduced to very small values and the data processed without any manual assistance. This technique is currently used with radar and laser trackers.

On air-combat training test ranges, in addition to the previous tracking systems, simultaneous tracking of multiple targets equipped with special instrumentation pods is also currently practiced to enhance training safety, efficiency and economy. It consists of measuring the vehicle distance to a network of fixed stations (multilateration technique) and processing in real-time the data transmitted to a central processor/controller.

It is hoped that all these systems will be complemented in the near future by fully computer controlled time/space positioning systems of improved accuracy, consistent with the latest navigation and weapon system requirements.

(iv) Airborne processing and/or ground processing of telemetered data

* Pulse duration modulation (PDM), pulse amplitude modulation (PAM), etc...; for high frequency recording (20 kHz bandwidth) in particular in noise measurements, direct recording remains a current practice.

Large aircraft have no weight or volume limitation during the flight test stage to prevent installation in the aircraft of on-board processors, storage equipment (tapes, disks, printers, hard copy, etc...), display terminals (alphanumeric and graphic terminals, analog and digital indicators, etc ...) or of the needed flight test personnel. On-board, on-line, real-time data processing can be performed at least partially and a selection made of the most important measured parameters, conveniently processed, and displayed to the flight engineers and to the flight crew. Thus, an accurate monitoring of the flight test program can be effected in close cooperation between engineers and flight crew.

With volume and/or weight limited vehicles, such as fighters, missiles, RPV's etc..., where problems are encountered even in installing the data acquisition system, the alternate solution to on-board data processing is to transmit the data to a ground based data processing facility via a telemetry link. As for on-board magnetic recordings, numerous time division multiplexed digital data and frequency division multiplexed analog data can be transmitted through one or several telemetry frames. Received at the ground station, the data are demultiplexed, demodulated and, through a proper interface, routed to the ground computer system to be processed and displayed to the ground test team in real-time.

Simultaneously two other operations are generally performed: the received telemetry signal is recorded on magnetic tape as a safety procedure against possible failures of the on-board tape (notwithstanding the additional telemetry noise, the content of this tape is similar to the on-board recorded signal); the analog data must be converted to digital form by analog-to-digital converters and the whole set of digital data reformatted to a standard computer-compatible magnetic tape.

This process, delivering magnetic tapes for any level of analysis by batch processing, can be performed on-line either on the aircraft with airborne computers, or on the ground through the ground processors (on-line with the telemetered signal, or by play-back of the flight tape after the flight, when no airborne computer able to perform this formatting is installed on-board).

Frequently, telemetry is used even when an on-board processing system is installed on the aircraft, in particular when it is desirable to operate with reduced flight crew due to the hazardous nature of the tests, as in flutter or other types of flight envelope opening. It is pointed out, moreover, that when comparing on-board processing with ground processing (the only choice for certain vehicles) one can find advantages and disadvantages to both solutions.

The advantages of the on-board processing are as follows: the direct contact between test personnel and flight crew in a true flight environment can help to appreciate correctly the flight situation; the possibility to display the processed data to the crew can improve the accuracy of the flight test exercises; and the autonomy of the aircraft in respect of a ground station allows the tests to be performed in the best available geographical area, hence with less weather constraints.

The disadvantages are: weight, volume and power supply limitations even with modern equipment (except for large airplanes); the need to have as many on-board equipments as airplanes tested, to assure flexibility to properly combine test programs; and limitations in numbers of flying specialists.

The advantages of the ground processing systems are as follows: no practical weight, volume or power supply limitations on the ground; when several computers are available to test several airplanes simultaneously and an increase of computer power is useful, the possibility to connect several computers; it is also possible to connect peripheral processors to the mainframe computer to share the processing work; the possibility to install a larger number of displays in the test control room and to monitor complex tests with the participation of all the required specialists; and minimizing the number of flying personnel is also an important favorable safety feature. The disadvantages are the following: no autonomy with respect to the test center and requiring additional equipment for currently needed tests in remote areas (tests at extreme temperatures, for example); inaccuracies or loss of the telemetry transmission when flying at very low altitude and/or performing tight maneuvers; and cost of the telemetry equipment.

This discussion shows that there is no absolute optimum choice between on-board and telemetry data processing. For large aircraft testing, where most of the disadvantages of on-board processing are irrelevant, this option, with limited telemetry for special tests, appears more appropriate. For flight test centers dealing simultaneously with several specimens of many types of aircraft and of course with missiles, real-time ground processing of the telemetered data is the preferred and frequently the unique solution.

(v) Data processing

Data processing equipment, essentially computers and their peripherals, is operated at the following levels: preprocessing, on-line processing, display and editing, and batch processing.

Preprocessing is performed on-board or on the ground during flight or by playing back on-board magnetic tapes after the flight. Generally it includes the following operations: selection of the data to be processed (on modern systems most of the data are preprocessed), analog to digital conversion (if applicable) of the recorded analog signals, data compression (if applicable), smoothing, filtering, data validation, time correlation, conversion to engineering units, and production of computer compatible magnetic tapes.

Usually, properly interfaced minicomputers are provided to perform these preprocessing tasks. These minicomputers must be structured to have: high input/output/throughput rates, numerous external interrupts, relatively low base cycle time, numerous CPU registers and buffered memories, real-time monitoring capability, and high instruction rates, supplemented by large capacity storage devices (disks, floppies, etc...).

On some installations the preprocessor computing power is sufficient to carry out some additional work, such as computation of fully corrected in-flight parameters, aerodynamic, propulsion and structural characteristics, etc... In other cases, on the contrary, it is more practical to carry out part of the previous preprocessing work on a general purpose computer directly connected to the preprocessing system.

Thus, how to share the preprocessing task and part of the on-line analysis work between minicomputers (sometimes super-minicomputers) and a connected general purpose central computer is a matter of organization, hardware availability and cost effectiveness. Today's state-of-the-art airborne preprocessors have relatively limited computing potential, and the practice with these processors is to relay on limited airborne processing followed immediately after the flight by detailed and/or high level processing of the computer compatible magnetic tapes (large airplanes). With a real-time telemetry system preprocessing, and an important part of the analysis, can be performed on the ground on-line using super-mini computers, with 2 to 3 simultaneously flying vehicles.

At large test centers, where several vehicles are flying at the same time, using a common ground installation, preprocessing is usually made by a network of processors connected to a large general purpose computer. With this system on-line storage on disks can also be done in addition to producing computer compatible tapes, allowing subsequent rapid batch processing on large central scientific computers.

In addition to preprocessed data obtained as time-histories of various measurements in engineering units, safe and efficient flight test monitoring requires fully processed data of a number of important parameters in order to carry out several functional analysis related to the particular test exercise. Editing of the computer outputs in easily interpretable forms, as time histories, parameters y versus x, out-of-limit warnings, etc., and presenting these data on interactively operated alphanumeric and graphic displays, on listings, stripcharts, paragraphs, hard-copies, etc., will help the test team in validating the data in deciding appropriate corrective actions in case of discrepancies.

All these operations are computer controlled using specially developed processing, displaying and editing system software in conjunction with the computer operating system. Preparation and checkout of the software library is a very expensive item representing an important part of the pre-test phase of the flight test program and takes usually several man-years. It is equally important, with the rapid evolution of computer hardware, to update the equipment periodically in compliance with the particular needs of the test programs, using the latest cost-effective developments of the computer market.

This type of utilization of modern data acquisition, computer and display technologies in real-time testing environments, in combination with the judgment and reasoning ability of human operators, results in large increases in flight testing efficiency and in significant time and cost savings.

Detailed analysis of flight test data is a particularly important area in the data handling process. The results of this analysis will provide the data base to judge the value of the product from the designer and user viewpoint, to check that design specifications are met, to decide the type of corrective actions if and when required, and to initiate, in agreement with the customer, cost-effective product developments and refinements. In addition, after developmental testing and evaluation and the subsequent configuration freeze, the analysis of certification and operational test results will constitute the documentation for flight test manuals, user's manual, etc... Detailed analysis, carried out either within the flight test organisation responsible for the test program, or by specialists belonging to engineering design groups of the vehicle, is generally effected by batch processing. Except for relatively limited flight test programs, this work is done on large mainframe computers.

The data source for this operation is the computer compatible magnetic tape or magnetic disk, obtained during the on-line preprocessing or in off-line mode using the preprocessing software, by playing back the airborne or telemetry recorder tapes after the flight. These tapes frequently originate from numerous different sources, recorded on various formats (airborne or telemetry tapes, time/space tracking records, weather data, system outputs from digital avionics and weapon systems). A special data merge software is applied to synchronize and store all the pertinent data on a common basis. The primary function is to conduct special calculations defined for the particular flight trial from selected test data. The output of most of these systems will be in the form of tabulated listings or plots and special programs are available to handle this particular aspect of the analysis.

Typical application areas, requiring specially developed software packages, are general aircraft parameter time history programs (as in on-line processing: weight, CG, airspeed, altitude, temperature, etc...), propulsion and performance characteristics, stability and control parameters derived by steady state measurements or by more elaborated parameter identification techniques,* time/space position information, in particular take-off and landing flight path data for performance and noise analysis, static and dynamic structural measurements, subsystems and weapon systems evaluation, etc...).

The software library covering these topics, in conjunction with a properly sized general purpose computer and editing system, constitutes a fully automatic and cost-effective means in responding efficiently to all the designer's and user's requirements.

(b) Developments and Future Advances

The most important aspects, with an increased emphasis on the role of computers in real-time and batch processing of flight test data, will be discussed in the areas of (i) advances in data acquisition systems, (ii) future time/space positioning and communication systems, and (iii) the role of the computer in future flight data systems.

(i) Advances in data acquisition systems

A trend, which is a direct result of progress made in microelectronics, is the tremendous growth of data recorded in digital form (PCM), as opposed to the analog FM recording. There are many advantages in digital recording, the most important being higher accuracy (a dynamic range of 60-70 dB vs 40-50dB for analog), better compatibility with digital computers, capability to multiplex numerous measurands and less stringent requirements for recorded signal quality. These are the main reasons why PCM is more and more popular in current flight test recording. There are however test situations where many simultaneously acquired measurements (50 to 100 parameters, sometimes more) with a large bandwidth (10 to 20 kHz) are required as in vibration and noise, propulsion/airframe compatibility studies, etc... The large PCM throughput, sampling rate, data storage and tape bit density requirements are difficult to meet economically with today's technology equipment. It is believed that, with computer aided formatting and further miniaturization, relatively near-term advances will provide a satisfactory solution for these problems.

(ii) Future time/space positioning and communications systems

Time/space positioning systems utilize external measurement systems such as cinetheodolites, radars, laser trackers, multiple sensors, or internal measuring equipment such as airborne cameras, inertial navigation systems, etc... Some of this equipment is very manpower expensive

* Parameter identification is a particular application of mathematical modelling and system identification techniques (see for example AGARD Lecture Series 104).

and consequently impractical. Accuracy of cinetheodolites and laser trackers is satisfactory at short range, but the radars used for longer ranges are only marginally acceptable. In particular, it appears that current navigation systems are more accurate than the test range equipment evaluating their performance. Enhancement in accuracy is expected from an integrated system with the future Global Positioning System, which will provide a capability for accurate time/space position information and telemetry of single and multiple aircraft.

Communication includes voice, video and data communications. There is a requirement in many flight test programs to insure real-time communications betw en multiple measuring stations of the flight test base on relatively short range and sometimes for long distance communications between remote stations. For the short range communications and high bit rate transmission, fiber optic wiring is frequently adopted. For long range purpose, satellite technology constitutes the future solution.

(iii) The role of the computer in the future flight data systems

It was shown in the previous paragraphs that the whole spectrum of computers, from microprocessors to supercomputers, can play an important role in the modern automated flight data handling process. Operation of these computers is generally partitioned between various tasks, such as data acquisition, preprocessing, on-line processing and data display and finally detailed analysis in batch processing mode.

This modular structure is likely to remain unchanged in the near future, but spectacular advances are expected from computer applications of microelectronic technologies as VLSI and VHSI circuits. Miniaturization of computers, increase of their speed and storage capacity, decrease of weight, volume and cost will allow to satisfy future test program challenges of increased number of measurands, higher accuracies and more thorough data analysis carried out in reduced time and at limited costs.

The data system configuration will depend on the type and size of the testing organization (university, large research organization, industry, government test center, etc...) and on the size of the the program considered (single vehicle limited purpose tests, aircraft or missile development program, multi-aircraft testing environment). These applications are discussed below.

With regard to data systems for single vehicle and limited purpose tests the number of parameters measured is relatively limited (10 to 50). From the computer viewpoint, this will be the privileged area of microprocessors. In view of limited real-time processing and data display, the computer can have a multiprocessor architecture with shared memory. Systems under development include cassette or cartridge type magnetic recorders. In some cases solid state memory devices are interfacing in the magnetic tape formatting procedure. Detailed post-flight analysis, when required, can be easily done on a small or medium size minicomputer. Future advances certainly will bring an additional increase in the number of measurands and a decrease of costs.

Data systems for development flight test programs, historically the first in the area of automated data acquisition and processing, includes telemetry systems with the capability to test single aircraft; telemetry systems with the capability to test a limited number of aircraft flying simultaneously (2 to 3); and airborne data systems, where the on-line processing and display are carried out on-board, telemetry being used only for special tests. These represent a large part of industrial and research activities in flight testing.

In all these systems the computer executes multiple tasks during the tests, these tasks being managed and carried out in a proper order and timing. The solutions chosen in modern systems is a super-minicomputer taking the whole workload, or a network of minicomputers sharing the various tasks in an optimal manner. It is important to mention that if there are some variations between computers in ground telemetry and on-board computers, there is no super-minicomputer selected for these tasks.

The main reasons are: a large part of on-line processing consists in manipulating huge dataflows executing relatively few mathematical operations; this is not a well-adapted task for supercomputers; on the contrary, modern minicomputers have input/output channels with programmable processors, very high throughput rates, powerful instruction sets and therefore are well adapted to the previous tasks. Progress in minicomputer technology is at least as rapid as in the area of general purpose large computers, and it is believed that they will constitute an excellent, flexible and economic answer to future flight test requirements. With the continuous development of microprocessors, a distributed network of microprocessors will be able to relieve the minicomputer from part of the processing task, thus giving the minicomputer the capability to execute higher level analysis. Finally, specially structured processors, such as Multiplex Processors, Array-Processors and Smart Display Terminals can be connected to the minicomputer giving the system a significantly enlarged performance. For all these reasons the number of microprocessors and minicomputers is likely to increase in future data systems.

Although the previously defined system based on minicomputers also has batch processing capability for higher order analysis, it is generally more practical and economical to use for this purpose a large computer with the computer compatible magnetic tape or other storage devices as data sources. It is probable that this situation will prevail unchanged in the foreseeable future, the increased data flow resulting from the increased complexity of future test programs will more than offset the overall processing capability of the minicomputer based data system.

It is concluded that the development of general purpose large computers will provide an enhanced batch processing capability for the present systems. In addition, the natural continuous increase in computation capabilities of the engineering teams will also contribute to meeting future flight test data processing needs.

Regarding data systems for multi-aircraft testing and training, a number of testing organizations (principally in the USA) require the capability of testing simultaneously several aircraft and/or missiles using common telemetry and other ground-based measuring equipment. Similarly, in multi-aircraft air-combat training ranges, instrumentation tracks many aircraft in real-time in position, velocity, etc...; other parameters are telemetrered and the results displayed for combat evaluation and monitoring. They are also recorded on magnetic tapes for post-combat debriefing. Although these two activities are not identical, there are sufficient similarities between them, in particular in computer requirements, to limit the discussion to a typical data acquisition and processing system of a large government flight test center.

On aircraft tested at these centers, the on-board data acquisition system, from the sensors to the downlink temeletry emitter, has the same structure as in the single aircraft testing case. On fighters, with limited available volume, some tradeoff must be accepted presently, but near-term advances in miniaturization of measuring equipment seem very promising and it appears that even with a reasonable increase in the number of measurands, fairly large volume and weight savings will be possible.

The ground telemetry consists of multiple receivers (one per frame) demultiplexers, demodulators and a distributed network of mini-computers connected to a large mainframe computer. The mini-computers receiving the telemetered signals from several aircraft carry out the preprocessing work, transfer the preprocessed data in shared memories of a dedicated minicomputer, which directs the results to the large computer and also to various computer controlled displays. The large computer executes several simultaneous operations: it stores the data in engineering units on disk and/or magnetic tape and performs more tedious calculations which are above the minicomputer capability.

Thus data analysis, with all the desirable details, will be made by batch processing on various large scale computers with the disk or digital magnetic tape as data sources.

As it appears from this discussion, the large-scale computer of the data system, even supported by the minicomputers, is heavily loaded. An increase of capacity and speed would be certainly helpful, and it is in this area that supercomputers can upgrade the efficiency of the system. However taking into account the responses to the questionnaire, it appears that even in this intensive computerized environment, there is no strong requirement for a very large increase of the computation power of the mainframe computer. It seems that natural technological advances in computer speeds and memory capacity will provide a satisfactory solution.

2.4.4 General Remarks

This review of the current and future role of computers in simulation and flight testing has been conducted with the aid of questionnaires circulated to the technical community in Europe and the US, through members of the Flight Mechanics Panel of AGARD. Substantial information has been acquired and analysed through these means and a great deal of insight provided into the ever-increasing role of computers in both flight simulation and flight testing.

With regard to simulation, the survey results highlighted the strong relationship between computational fidelity factors, level of model complexity, vehicle type, intended usage of the simulator and required computer performance capabilities. It was shown that a high level of computer utilization has been reached and that current in-place computational power dedicated to real-time simulation (including visual image processing) ranges between .2 Mflops and 10 Mflops depending on the particular facility surveyed.

A substantial fraction of the simulation community surveyed indicated plans to upgrade or expand current computer assets to meet future application needs and opportunities. Reasons cited were: increased flexibility and improved price-to-performance ratio afforded by new technology, increased computing bandwidth, improved performance of digital-analog linkage and interfaces, obsolesence, and improved model fidelity. In this regard, the rapid development of microprocessor technology is expected to have a dramatic impact on real-time simulation computing architectures i.e. tightly coupled concurrent distributed networks uniquely configured for simulation applications may soon be achieved.

Based on the evidence collected during this study, a convincing case cannot be made for especially developed supercomputers utilized solely in the real-time simulation support role. However, rotorcraft simulation and future prospects for high fidelity visual scene simulation (CGI) appear critical from a computer performance viewpoint. The simulation of high performance compound helicopters, utilizing reasonably complete rotating blade element models including rotor-fuselage interference characterization, requires computational speeds of 12-15 Mflops to achieve computational fidelity of the highest frequency mode present in the vehicle response. The real-time simulation of multi-rotorcraft gaming environments, with equivalent model fidelity, would pose severe computational requirements. However, these requirements could be satisfied by current Class 6 machines. Table 1 summarizes the various estimates of computer requirements for specific simulation tasks and vehicle types.

The equivalent computing power requirements for future Computer Generated Image (CGI) systems will be massive (estimated as 10^2 - 10^4 Mflops for systems of several hundred thousand edges). However, these systems are expected to remain highly specialized computing devices and not useful for general scientific application. General purpose computers with adequate performance capabilities will not be economically acceptable in the CGI support role. The future of CGI lies with VLSI technology and developments in high density optical disks to replace magnetic disks.

Expected developments in electronics technology will provide opportunities to ameliorate increased computational requirements posed by new and expanding simulator applications. These computational requirements, when compared to the severe demands inherent in computational aerodynamics, do not appear to be a first order effect in the supercomputer equation. However, when such super-computing machines are developed, flight simulation could benefit for specialized applications.

With regard to flight test data systems, it is clear that a strong relationships exists among the various elements of these systems, i.e. data acquisition equipment, telemetry, ground based measuring equipment, displays and computers (hardware and software). It is seen that a high technological level has been reached in most areas and, in order to respond to increased future requirements, properly balanced advances, are necessary.

Concerning more particularly the computers themselves, it appears very clearly that the advent of minicomputers and microprocessors and their rapid development have had a dramatic impact on flight test instrumentation and processing. It is in this direction that the largest further advances are expected. Large computers are strongly needed for batch processing and in the multi-aircraft testing environment. However compared to the severe requirements of computational aerodynamics, flight testing does not appear as a strong driving force for supercomputers.

TABLE 1

ESTIMATED COMPUTER REQUIREMENTS FOR VARIOUS SIMULATION TASKS

VEHICLE TYPE AND SIMULATION CLASS \ COMPUTATIONAL PARAMETERS	$N_o \times 10^{-4}$	F HZ.	S_c	P_s	* DFLOPS $\times 10^{-6}$
CONVENTIONAL TRANSPORT	2 - 4	1.5	20	$\frac{1}{4}$	.6 - 1.2 2.4 - 4.8
HIGH PERFORMANCE FIGHTER & WEAPONS	4 - 5	3	20	1	2.4 - 3
ACM FIGHTER x 2 & WEAPONS	5 - 10	3	20	1	3 - 6
ROTORCRAFT	4	**17	20	$\frac{1}{4}$	13.6 ≃ 54
MULTI-ROTORCRAFT GAMING ENVIRONMENT ROTORCRAFT x 2	8	17	20	1	≃ 25

*EQUATION 3

**5 BLADE ROTOR (ROTOR SPEED 200 RPM)

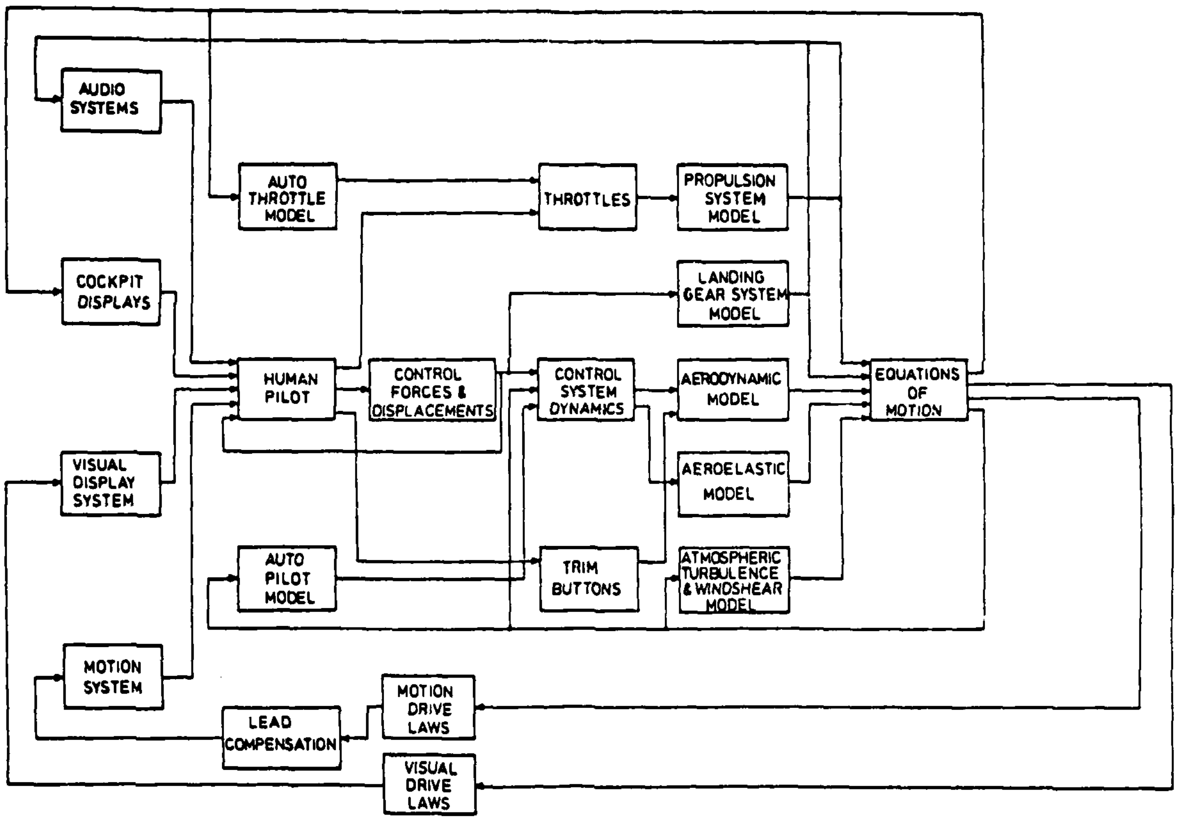

Figure 1.- Block diagram of piloted flight simulation.

STATES	INERTIAL, STRUCTURAL, AERODYNAMIC, ACTUATOR FLOW, TEMPERATURE DYNAMIC VARIABLES	$\dot{x}(t) = f(x,u,\theta,t) + w(t)$
MEASUREMENT	ANGULAR AND LINEAR VELOCITIES, ACCELERATIONS, TEMPERATURES, PRESSURE, ROTOR SPEEDS, ACTUATOR/SENSORS	$z(t) = g(x,u,\theta,t) + \zeta(t)$
CONTROL:	SURFACE POSITIONS, DYNAMICS, FILTERING	$\dot{u} = p(u,z,t) + \varphi(t)$
OUTPUT.	AIR FLOW, THRUST, DRAG, SPECIFIC FUEL CONSUMPTION, SURGE MARGIN	$y(t) = h(x,u,\theta,t) + v(t)$
RESPONSE	DESIRED ATTITUDE, POSITION, VELOCITY, THRUST, THRUST RESPONSE	$r(t) = g_r(x,u,\theta,t)$
REMARKS.	STATE EQNS TYPICALLY FIRST ORDER NON-LINEAR DIFFERENTIAL EQUATIONS FLOW EQNS MAY INCLUDE TIME DELAYS CONTROL EQNS INCLUDE LINEAR AND NON-LINEAR FILTERING NON-LINEAR MEASUREMENT AND OUTPUT EQUATIONS NOISE CHARACTERISTICS APPROXIMATED-N(O,Q) AND SPECTRALLY SHAPED	

Figure 2.- Component modeling for simulation.

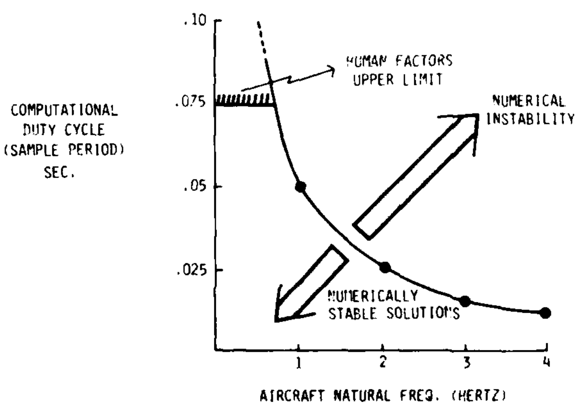

Figure 3.- Computational Duty Cycle for Real-Time Simulation of Fixed Wing Non-Aeroelastic Aircraft.

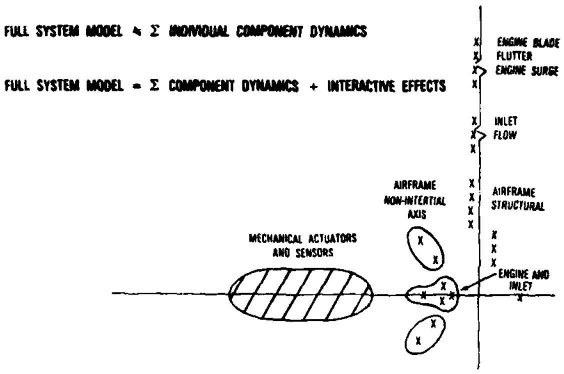

Figure 4.- Characteristic ROOT Distribution for Full System Simulation Models.

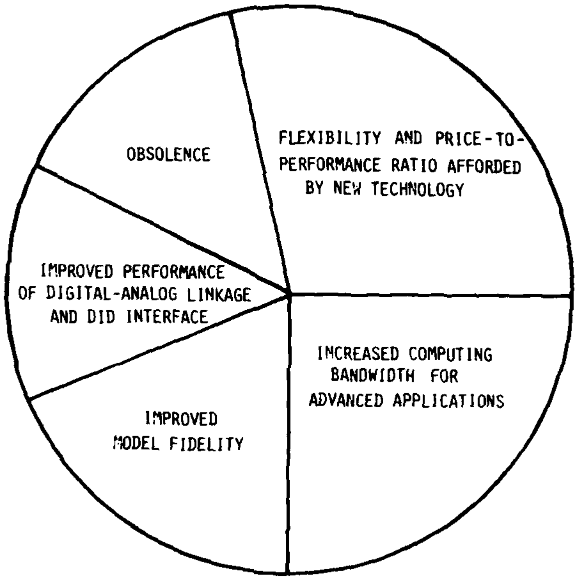

Figure 7.- Survey responses citing reasons for up-grade of current computer assets.

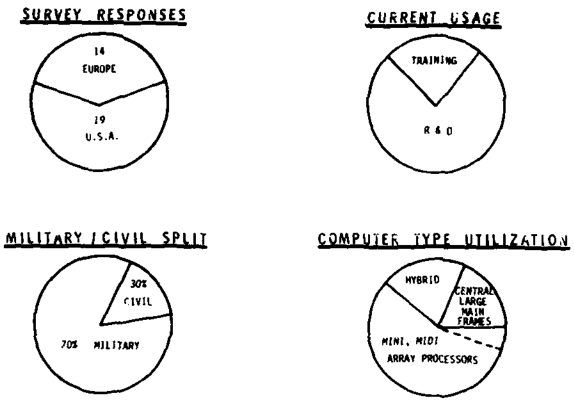

Figure 5.- Survey summary.

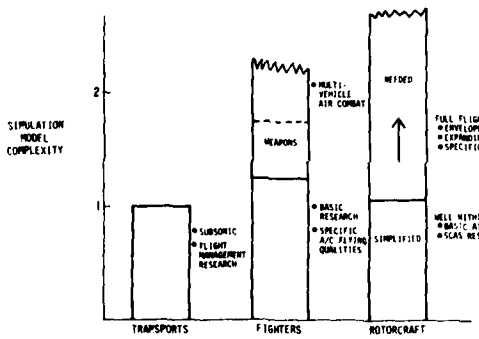

Figure 6.- Model complexity vs. vehicle type.

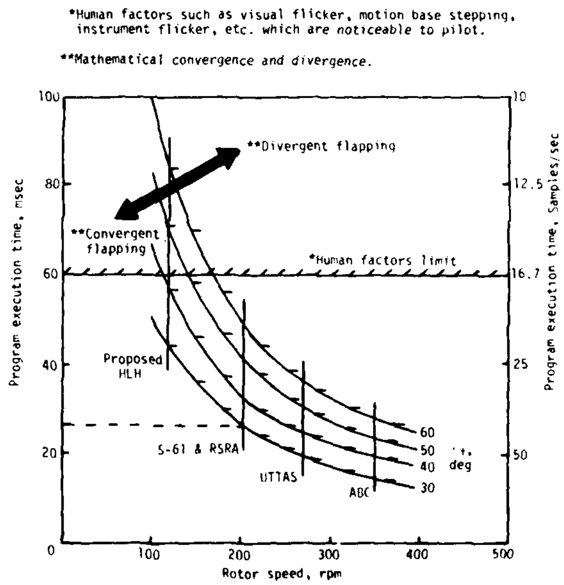

Figure 8.- Effect of rotor speed and azimuthal update on allowable program execution time for flapping convergence.

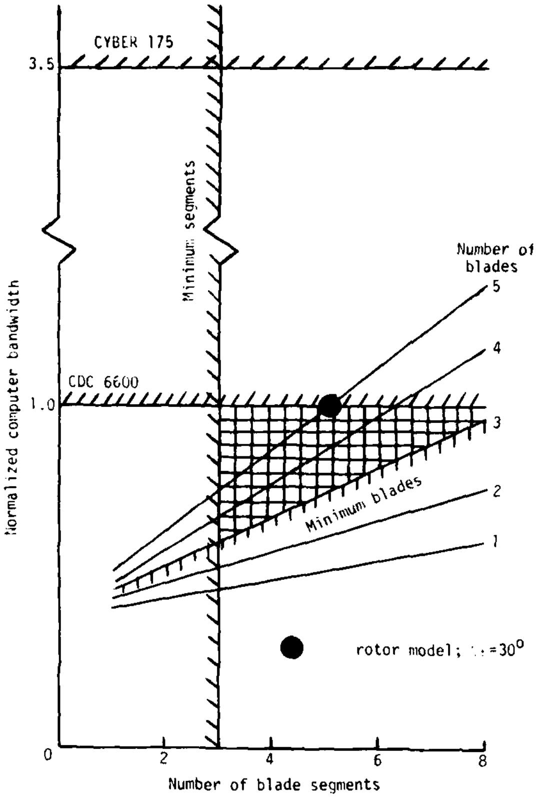

Figure 9.- Comparison of program execution time for a CDC 6600 computer with a CDC CYBER 175 computer for a five-blade, 200-rpm rotor model.

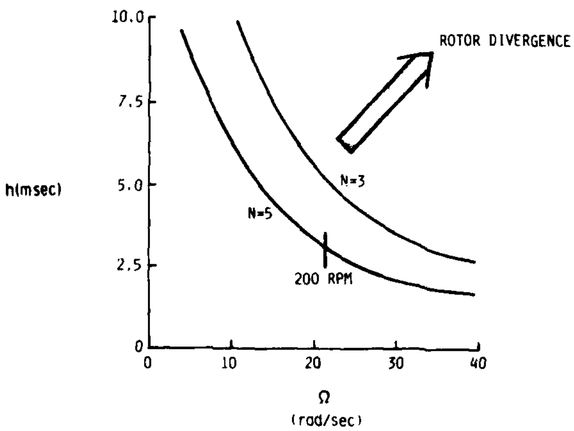

Figure 10.- Estimated computational interval to achieve dynamic fidelity for rotorcraft simulation.

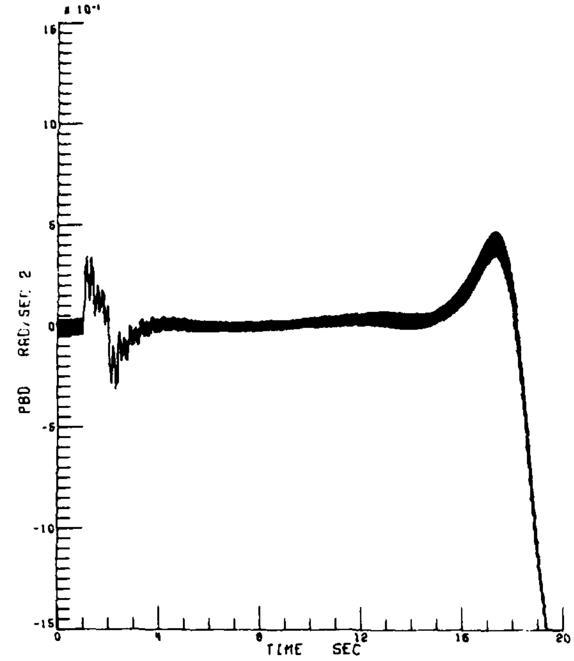

Figure 11.- Roll acceleration dynamic response for (5b x 5s) rotor, computational interval 1/240 sec.

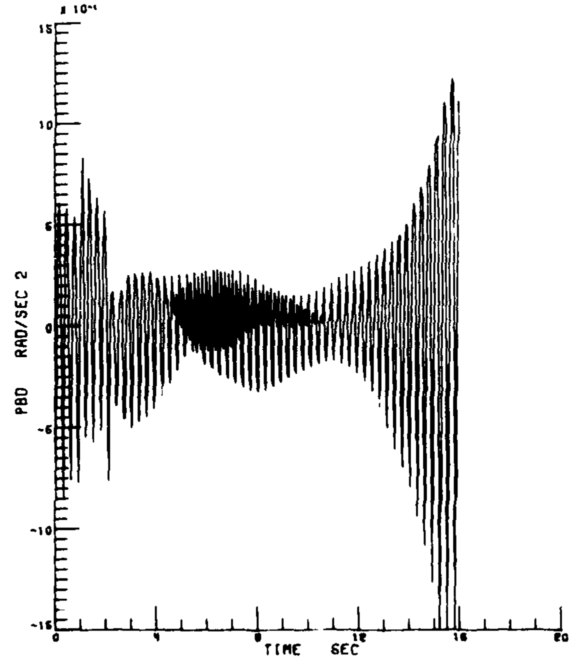

Figure 12.- Roll acceleration dynamic response for (5b x 5s) rotor, computational interval 1/20 sec.

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Appendix 2.4.1: Organisations Responding to Survey Questionnaires

FRANCE

Aerospatiale, AMD-BA, Celar, C. E. V., L. M. T., Matra, Thomson CSF, Sogitec,

ITALY:

Aeritalia, Augusta, Italian Air Force

NETHERLANDS:

N. L. R., Fokker

UNITED KINGDOM:

British Aerospace, RAE

FEDERAL REPUBLIC OF GERMANY:

Dornier, DFVLR, Technische Hochschule Darmstadt, BWB, MBB, TABG, HSBW, VFW

UNITED STATES:

Naval Air Test Center, Arvin/Calspan, NASA Langley Research Center, NASA Ames Research Center, Bell Helicopter (Textron), University of Kansas Center for Research, Inc., Dryden Flight Research Facility, Boeing Company, Boeing Computer Services Company, U.S. Air Force, Wright-Patterson, U.S. Air Force Flight Test Center, Lyndon B. Johnson Space Center, General Dynamics, Convair Division, U.S. Army Aviation Research and Development Command, Fairchild Republic Company U.S. Air Force Human Resources Lab, Lockheed-Georgia Company, Rockwell International.

Appendix 2.4.2: Questionnaire on Computer Requirements for Simulation

Quantitative data or narrative explanations are solicited in response to the following questions:

1. WHAT TYPE OF SIMULATORS ARE YOU OPERATING?

   General purpose simulators.

   - General research.
   - Design and development of transport aircraft (civil and military).
   - Design and development of fighter/bombers.
   - Design and development of rotorcraft.
   - Design and development of missiles.
   - Air traffic control interfaces with above vehicle types.

   Combat simulators.

   Training simulators (civil and military)

   - Flight training.
   - System familiarization.
   - Procedures.
   - Mission training (including combat tactics).

   In-flight simulators.

   Others.

2. TYPE AND BRIEF DESCRIPTION OF YOUR SIMULATOR COMPUTER SYSTEM.

   Main characteristics and facility configuration.

   - Distributive vs. large main frames.
   - Age of your present real-time computing system.
   - Is it used at full capacity?
   - If not, date when the full capacity usage will be reached.

3. ARE YOUR PRESENT REAL-TIME COMPUTER HARDWARE AND SOFTWARE CAPABILITIES-

   (a) Sufficiently time-responsive and cost-effective for today's and future simulation needs?

   (b) Limited by available performance in some type of simulator application (examples)?

4. MEANS TO UPGRADE YOUR SIMULATION CAPABILITIES FOR FUTURE NEEDS AS FAR AS THE COMPUTER ELEMENTS ARE CONCERNED-

   (a) By keeping the existing equipment and increasing the speed and capacity by additional equipment.

   (b) By changing to more powerful computers.

   (c) By changing to new types of computers with different architectures and how and when you intend to carry out this upgrade.

5. IDENTIFY UNIQUE AREAS WHERE SOFTWARE DEVELOPMENT APPEARS NECESSARY FOR YOUR FUTURE SIMULATION NEEDS.

   Programing support environments (language, debuggers, editors, etc.).

   Configuration management tools.

6. RANGE OF VALIDITY AND COMPLEXITY OF THE MATHEMATICAL MODEL USED.

   Aircraft dynamics and missile dynamics.

   - Simplified or exact kinematics and mass properties.
   - Simplified (more or less linearised) or complete nonlinear aerodynamics.

   Structural dynamics.

Aeroelastic effects at low frequencies (if applicable).

Rotorcraft simulation.

Active control.

Propulsion system characteristics.

Forces and moments vs RPM and condition of altitude, temperature, Mach number.

Dynamics: time response to control inputs.

Flight control systems.

Mechanical characteristics (friction, hysteresis, etc...)

Displacement and control feel.

Control system dynamics.

Automatic stabilization and control system, control laws.

Navigation systems.

Ground based: VOR, TACAN, ILS, MLS, GPS, etc...

Onboard: INS, radar, FLIR, etc...

Weapon systems

Firing-launch-release logic.

Weapon trajectory computation.

ECM, ECCM.

Other Aircraft systems.

Electrical/hydraulics.

System failure/redundance.

Displays

Flight director computation modes and logic.

CRT displays, EADI, energy management, moving maps, etc.

HDD and HUD

Symbol generation and display logic.

Environment.

Atmospheric statics (variation of temperature, pressure and density with altitude).

Atmospheric dynamics (wind, turbulence, windshear and vertical drift).

Takeoff and landing simulation.

Ground effect.

Landing gear and tire dynamics.

Turbulence and windshear.

Runway surface conditions.

Are current technology computers satisfactory for these models, or is there a requirement for technology development?

7. COMPUTATIONAL DYNAMICS

Computation update rate (range of eigen-values).

Analog-digital interfacing.

Filtering and integration algorithms (are there special needs).

Input/output lags (how much is acceptable)?

Is there a need to develop specialised computers and softwares to improve computational dynamics of the simulators.

8. VISUAL SYSTEMS

Image generation and display.

Camera-modelboards (TV or laser display).

- Computer-generated imagery (TV or laser display).
- Film.
- Shadowgraph.
- Type of optics, field-of-view, resolution, etc.

Computer related problems in CGI.

- Computer characteristics.
- Image information content.
- Image deficiencies.

How CGI can benefit from the following computer technology developments:

- Increase in computing speed.
- Parallel and vector processing.
- VLSI techniques.
- Improvement of computing algorithms.
- New scene generation programing techniques.

Is there a need to develop in the future specially structured computers for CGI and would such a development be economically acceptable?

Appendix 2.4.3: Questionnaire and Responses on Flight Testing

In this Appendix the responses to the questionnaire on Flight Testing are examined and general conclusions indicated:

Question 1: TYPE OF DATA ACQUISITION USED IN YOUR FLIGHT TESTING ORGANIZATION?

(a) Telemetry

(b) On-board recording

(c) Others (ground tracking equipment, high speed cameras, etc...) cinetheodolites, radar, video-camera

(d) Video-camera

Answers: Except for small organisations, both telemetry and on-board recording is used. However emphasis is on on-board recording on large airplanes. On-board optical and video-cameras are largely used, video images are sometimes telemetered. Large test organizations always have available ground tracking equipment such as cinetheodolites and/or radars, and frequently also laser trackers. In some cases multichannel ranging devices are used.

Question 2: TYPES OF RECORDING?

(a) Magnetic tapes

(b) Optical systems

(c) Solid state memory devices

(d) Others: cameras, video-cameras

Answers: Magnetic tape recordings are used by all organizations, in the large majority 14-track, 1-inch wide, sometimes 28 track. Optical recording, strip charts mostly as backups or quick-look, video-recording in image mode. Digital computer compatible tapes or disks produced on-board on large aircraft. Solid state memories in combination with tape, cassette or cartridge.

Question 3: NUMBER OF PARAMETERS RECORDED (TYPICAL FIGURE, DEPENDING ON THE PARTICULAR DEVELOPMENT PROGRAMS)?

Answers: The number of parameters recorded varies from values as small as 10 to several thousand (about 3500 in the extreme case). Typically 50 to 100 for limited purpose tests, 500 to 1000 in aircraft development programs.

Question 4: AGE OF YOUR PRESENT MEASUREMENT AND DATA PROCESSING SYSTEM?

Answers: They vary from obsolete equipment (sometimes 15 year old) to hardware in the developmental stage. Clearly a trend to keep the measurement and data processing system at the latest state-of-the-art level is shown, consistent with the rapid evolution of electronic technology, in particular in the minicomputer area. The financial and manpower burden in maintaining old equipment is also a driving factor to modernization.

Question 5: IS IT USED AT FULL CAPACITY?

Answers: It depends on the type of organisation: in the industry the system is generally used at full capacity, sometimes it is overloaded; in government flight test centers some reserve in capacity is kept in view of various unexpected problems; and in the research institutions the system is used at the pace of the research and development work.

Question 6: IF NOT, WHEN WILL THE FULL CAPACITY USAGE BE REACHED?

Answers: In the industry and most of the large flight test centers the equipment is used at full capacity. When not, various situations are prevailing: in some cases, deficiencies are being corrected to improve the situation, in others it will take several years before reaching the full capacity usage with the current equipment; at some centers new equipment is in development and full capacity will be reached in 2 to 4 years.

Question 7: IDENTIFY AND DEFINE THE CONFIGURATION OF THE COMPUTER SYSTEM USED IN DATA ACQUISITION AND DATA REDUCTION. DESCRIBE BRIEFLY THE MAIN CHARACTERISTICS.

Answer: The computers in preprocessing, in real-time processing, in displaying the data, range from large mainframe processors such as CYBER 74 or IBM 360/195 for the largest flight testing organizations to microprocessors, with a majority of mini-computer (PDP, SEL, XEROX) distributed network installation. On large airplanes, airborne processors (as ROLM, PDP, SFENA, ESD, MOTOROLA, etc...) can be installed for the same purposes, but with relatively limited possibilities. Numerous computer controlled peripherals are participating in the data presentation. Higher level data analysis is carried out on large mainframe computers (CYBER 74, IBM 30XX, AMDAHL 470, etc...) directly connected to the measurement system, or by batch processing after tape or desk transport or by special communication networks between the test center and a Central Computing Center. Performance of a minicomputer network can be enhanced for data analysis by connecting an array processor to the system. This is a cost-effective, flexible and modular solution for medium size Center. Performance of a minicomputer network can be enhanced for data installations.

Question 8: WHAT PROPORTION OF THE DATA IS PRESENTED IN QUICK-LOOK FORM, IN COMPLETE ON-LINE REAL-TIME OR AFTER OFF-LINE PROCESSING?

Answers: The answers vary from 10 to 100% for quick-look or real-time, the average being 30 to 40%.

Question 9: ARE YOUR DATA PROCESSED (PRELIMINARY AND/OR DETAILED)

(a) by the flight test division?

(b) by the various specialist teams concerned?

Answers: In most of the flight test organizations a limited quick-look analysis of the data and additional subsequent analysis is carried out by the flight test division itself. They are generally followed by detailed in-depth analysis made by the various engineering divisions concerned. Cooperative work between flight test and engineering divisions in data handling is a current practice in the industry. In developmental flight testing, part of the test program is sometimes resumed as the outcome of the data analysis. The final results will be retained as data base for design studies, simulations, product documentation, etc...

Question 10: ARE YOUR PRESENT COMPUTER HARDWARE AND SOFTWARE

(a) sufficiently time-responsive and cost-effective for today's and future needs?

(b) limited by their available performance in some type of data reduction (examples)?

Answers: Depending on the particular situation of the answering organizations, they vary from answers indicating that their hardware and software are neither time-responsive nor cost-effective and they are limited in performance, while at the other extreme a satisfactory situation for the present and foreseeable future is quoted. The difference results from the very different structures, tasks and missions of these testing organizations.

Large test centers are generally well equipped, but with rapidly changing requirements they have to update their hardware and software on a continuous basis. In view of future workload they have requirements for improved real-time graphics, enhanced interactive real-time computing capability, increased digitizing rate, high rate avionics testing capability, comprehensive data management system, etc... These organizations will have to expand their computer power by combining larger mainframe computers with mini-computers.

Medium-size organizations are generally working with minicomputers, sometimes superminis and with microprocessors. The flexibility and versatility of this type of system for data acquisition and real-time work, supplemented by batch processing on general purpose computers, is considered satisfactory for present needs and for the near future. It is also believed that the pace of advances in micro-electronics will be such that development of new generation of minis and micros will satisfy future requirements. A similar situation is expected from advances in the software area.

The unsatisfactory situation, which exists in smaller test organizations, is due to old obsolete equipments, most of them being replaced now by more modern, more reliable hardware which in addition is comparatively cheap. After this replacement, significant improvement in time-response and cost-effectiveness is expected.

Question 11: MEANS TO UPGRADE THE HARDWARE FOR FUTURE NEEDS AS FAR AS THE COMPUTER ELEMENTS ARE CONCERNED.

(a) by keeping the existing equipment and increasing the speed and capacity by additional equipment

(b) by changing to more powerful computers

(c) by changing to new types of computers with different architectures and how and when you wish to carry out his upgrading.

Answers: In cases where the present and near future situations are satisfactory, upgrading is scheduled by replacing present computers by their developed versions. Large centers are also considering changing their mainframe to more powerful computers and adding distributed minicomputer systems to satisfy heavy workload situations. All the other means suggested for upgrading will be practiced on a case by case basis, depending on existing equipment and program evolutions.

Question 12: IMPROVEMENTS REQUIRED ON THE DATA ACQUISITION, COMMUNICATION, RECORDING SYSTEMS AND DISPLAYS TO MAXIMIZE THE BENEFITS FROM THE COMPUTER HARDWARE UPGRADE.

Answers: The most important improvements considered are: automated airborne space positioning system; increased downlink speed (100 to 200 Kwords/sec); high PCM sampling capability; real-time graphics and interactive processing; high refreshing rate color displays, intelligent graphic terminals; electronic strip charts; high dataflow telephone lines; and direct bus message recording.

Question 13: IS YOUR SOFTWARE APPROPRIATE TO PRODUCE QUICK RESPONSE AND COST-EFFECTIVE RESULTS, IN PARTICULAR IN THE AREA OF:

(a) performance (aerodynamics and propulsion)

(b) stability and control (including modern FBW control systems, CCV, etc...)

(c) structural loads and deflection

(d) flutter and vibration

(e) weapon-system developmental testing

(f) navigation, terrain following

(g) acoustic measurements

Answers: Software is generally appropriate in particular organizations where the software needed can be developed and supported with a reasonable programming effort. However there are more significant deficiencies in the areas of: weapon system delivery and developmental testing, navigation, terrain following, and acoustics

Question 14: DEFINE PECULIAR AREAS WHERE SOFTWARE DEVELOPMENT APPEARS NECESSARY FOR YOUR FUTURE NEEDS.

Answers: In addition to steady development and maintenance of current application software and operating systems the following topics are suggested: application software to process large bandwidth digital data; data management software; computer aided flight test installation design; interactive simulation system interface; application software for future real-time analysis; tracking and communication software; software development methodology; high order computer languages; weapon systems testing software; data retrieval; and unified performance estimation packages.

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2.5. Integrated Aerospace Design

2.5.1 Introduction

In today's highly competitive environment, where the realization of optimum or near optimum products is an absolute prerequisite to success in the whole industry, design of aerospace vehicles is becoming an increasingly integrated multidisciplinary process. The rapid development of large scale computers and their cost-effective and routine use in aeronautics has evolved in the last two decades in numerous analysis, synthesis and optimization computer programs of various levels of sophistication in each individual technical discipline. However, in the past, attempts to integrate these computer programs into a single general purpose design process, encompassing every discipline concerned, were more the exception than the rule and were mainly limited to the early low level design stages.

This prevailing situation, clearly reflected in the Papers presented at the AGARD FMP Symposium on "The Use of Computers as a Design Tool" held in Neubiberg, Germany, September 3-6, 1979 (AGARD Conference Proceedings N° 280) is now changing toward design integration on both sides of the Atlantic, under the combined pressure of additional economical constraints and new technologies in parallel with further developments and prospects of future large scale computing systems.

To review the current status and likely evolution of the integrated design programs under development, a questionnaire was established and circulated in the AGARD community. The objectives of the questionnaire were to examine: the need, desirability and feasibility of design integration at various levels of the design process; the main reasons and driving forces for design integration resulting from computer and aerospace technology advances and developments; the most important benefits of design integration at the conceptual, preliminary and detailed design levels; problem areas which in the past prevented the development of efficient integrated computer-aided design programs; how new computer capabilities, hardware and software developments, will allow their solution; the possible hardware and software structures adapted to design integration; and possible schedules to implement these programs at various design stages.

Only a limited number of answers from (7 European and 5 US organizations) were received as a first step, due to various difficulties (large size and rapid evolution of the subject, short time available, etc...) and it was decided to carry out a second round of inquiry concentrating on the following questions:

> Is integrated design, or will it be in the near future, a high priority item in the various organizations consulted?
>
> Can implementation be realized on a progressive basis or after a special development effort of a total system?
>
> Is there any effort in design integration comparable with that in the past in computer aided graphics?
>
> What types and architectures of computers appear promising for cost-effective implementation of integrated design?

This section presents the analysis and conclusions drawn from the two questionnaires relating to the current and future role of computers in integrated aerospace design (see Appendix 2.5.1 for a list of questions and summary of responses). Responses were provided by 12 organizations in Europe and the U.S., representing both industry and government laboratories (Appendix 2.5.2). The integrated design process itself is discussed first and is followed by a review of the technology for integrated aerospace design including the needs, the means and the relevant computer requirements.

2.5.2 Definition of the Integrated Design Process

The numerous technical disciplines involved (aerodynamics, structures, propulsion and systems) and the economical, operational, environmental, and other factors to be taken into consideration, all contribute to the highly complex and multidisciplinary nature of the aerospace design process. In the past, to deal with such a complex situation, requiring in particular the manipulation and analysis of huge amounts of data, a large number of computer programs were developed in each individual discipline and were used iteratively in successive design cycles. However, synthesis between disciplines was mostly manual, and resulted in communication, data handling and interpretation problems, in possible loss of accuracy when dealing with interactive matters, in significant lengthening of the iterative design cycles and consequently in high overall design cost.

In contrast to these very undesirable working conditions, an integrated design is defined as a process attempting to assemble and to organize the whole design activity in such a computerized procedure where, at least ideally, each design decision is evaluated and worked out after due account has been taken of the effect of all the involved disciplines and of their possible interactions.

It is necessary to point out, that although in practice this definition, considered as a limiting case, cannot be applied yet completely, if ever, due to the inherent complexities of the aerospace design technology, it will be referred to as a final target in any integrated design process. Such a highly computerized automated methodology, because of its analysis, synthesis, optimization and evaluation capabilities, will constitute for the designer a very efficient decision-aiding, tool; decision-making however will remain entirely the designer's duty and responsibility. This type of synergistic man-machine relationship, an important characteristic of the integrated design technology, will be present at all conceptual, preliminary and detailed design levels.

2.5.3 Development of Integrated Aerospace Design Technology

Integrated aerospace design methodology is increasingly needed for the following main reasons: as a result of intensive worldwide computation, integration is becoming progressively mandatory to evolve advanced optimum or near-optimum aerospace products; to meet increasingly detailed and frequently conflicting mission and performance requirements, and severe economical, safety and environmental constraints; to deal with the trend toward more pronounced interactivity between aerospace disciplines which in past designs were considered separately; for more in-depth studies right from the conceptual design stage; for new and innovative configurations outside of current experience requiring the generation of an entirely new rational data base instead of using routine statistical data; to improve decision making by increased management visibility; early integrated studies will result in the minimization of late design changes; the possibility to carry out numerous multidisciplinary trade studies in an economic manner at the conceptual and preliminary design stages enables the designer to assess and evaluate an increased number of options before design freeze, giving him the opportunity to elect a better solution; the potential benefits resulting from unique engineering computerized data bases, including all required design information (geometry, material properties, tolerances, etc...) will provide an improved and better defined product; and to realize significant cost and time reduction and increased engineering productivity through the use of computer technology.

Although the manufacturing aspects were excluded from the Terms of Reference, and consequently are not dealt with in detail, it is worth mentioning here that a large part of the integrated design benefit is transferable to the computer aided manufacturing (for process and production planning, numerical control programming, robotics, etc...).

Turning now to the means for implementing integrated design, it is recognized that the design of a highly complex system, such as a modern air-vehicle, requires a fairly large computer even when using a conventional single-disciplinary design process. To deal efficiently with the tens of thousand inputs/outputs of current large size problems, access to the computer is generally made in an interactive mode through alphanumeric and graphic terminals. Accurate and efficient communication systems are also needed when several computers are involved in a distributed network structure.

Similar, but more highly developed, means will be required by the multi-disciplinary integrated design process to handle a much larger amount of data, to carry out all the relevant computational design tasks and to display the results to the designer in a readily understandable and interpretable form. Moreover, in the almost exclusively practiced interactive mode, system time response should be sufficiently short to minimize turnaround time and to allow examination of a large number of design alternatives.

Thus from the hardware standpoint, design integration will result from: large increases in computer speed and storage capacity (by orders of magnitude in case of supercomputers); improved input/output capabilities and from enhanced interactivity by better man-machine interfacing and machine-machine communication; increased data flow rate performance of communication systems; and advances in computer graphics and display technology (such as colored CRT's, three dimensional imagery, etc...). These features will be associated with an ever decreasing hardware cost, making the equipment more easily affordable.

Hardware compatibility problems, critical in the past, will decline in the future as manufacturers accept international standards. This provides the possibility for each specialist group to elect the hardware best suited to its particular task. In accordance with the importance of the task and of the design stage considered, computer size and performance can encompass a range extending from presently available midi-computers to the oncoming supercomputers and their corresponding terminals, displays and communication systems, the selected solution depending on availability, economics, etc.

The software for numerous aerospace application computer programs has been developed in the last two decades by the worldwide aerospace community, the industries,the universities and by research organizations, the process being continued at an ever increasing pace. However most of these programs, established for a single specific technical or scientific discipline,cannot be used directly in an integrated design environment, without being supported by a proper interfacing software and integrated in the complete design-software system. On the other hand, it appears clearly that such a high value asset, resulting from years of programming effort, cannot be replaced efficiently and in an acceptable time period by entirely new programs, but should be used with minimal modifications in relation with, and as part of, the integrated design software.

Implementation of this principle involves the following software developments: data management software to provide the capability for efficiently storing, tracking, updating, protecting and retrieving of large amount of data maintained on storage devices; executive program software to control user-directed processes and to provide communication between hardware in distributed computing systems; geometry and graphics utility software to provide a wide range of capabilities for information and geometry creation, data manipulation and user friendly display functions, and the creation of a company-wide data base complex containing a huge amount of design data, incorporating data processors for an easy access by all involved management and engineering personnel through the data management system.

This data base will also include project information concerning current baseline and alternate designs, handbook information, design criteria, manpower and cost scheduling, thus forming the organization's technology base. In addition, analysis, synthesis and optimization modules, collected from a number of selected sources will also be incorporated in the data base as will continuously used application programs in all stages of the design process. The data management software will ensure the proper interface between the modules and the required input data.

A modularly structured open-ended software system appears to be the best suited arrangement, permitting program development at a pace compatible with company needs, requirements and capabilities and ensuring all the desirable program evolutions with future computer hardware configurations. A time-consuming effort will be needed to solve numerous compatibility problems which will inevitably result from hardware related software particularities, programming language differences, non-standard programming techniques, etc... but the outcome will be a significant overall improvement of the design (and manufacturing) process when efficiently used by large engineering and management staffs.

Computer requirements for the integrated design process depend on the design level considered (conceptual, preliminary or detailed). Many industrial and research organizations are operating integrated programs currently on their existing computer equipment at the conceptual design level. Progress toward a certain degree of automated integration at the preliminary design stage is also continuing and the present generation large computer systems are generally able to meet the needs of preliminary design. Therefore possible limitations at this stage are rather due to lack of software development.

For detailed design much remains to be done on software as well as hardware development, but a large distributed computer network, consisting of one or several mainframes, linked with a large number of satellite processors through efficient input/output accessing and communication systems, is a convenient short time basis for this design level. The future advent of Class 6 and supercomputers will certainly be beneficial for the detailed design integration process under the condition that the trend observed up to now of decreasing computer costs is maintained and that software development costs also remain within limits. There are reasons to believe this will be the case with the expected technological developments.

2.5.4 General Remarks

Current and expected advances in aerospace and computer technology are strong driving forces toward design integration which is considered as a highly desirable, and even a mandatory, objective. At the conceptual and preliminary design level some form of design integration is practiced in several leading companies and research institutions, using presently available computers and specially developed software.

Implementation of the integrated design process at the detailed design stage requires a fairly large computer system with powerful input/output, communication and display capabilities. This requirement will be reasonably met by Class 6 computers in connection with properly fashioned peripheral equipment. In addition, development and maintenance of the necessary data base complex, data management, executive and utility software is a very large and long-term task. At this stage this seems beyond the financial and manpower capability of any single company or research institution. A possible solution of this problem may be the establishment of a consortium of organizations equipped with one or several supercomputers, interfaced with the computer systems of the associated members and providing large scale computation service and development, maintenance, updating and sharing of software according to commonly accepted operating rules.

A detailed study must be carried out, taking into account the requirements of all other parties interested in large scale computation, to define the exact structure of such an organization and the relations between its members.

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15. J. Czinzenheim: Modern Aircraft Design and Testing Technology, French Aerospace Seminar in India, 1981.

Appendix 2.5.1: Responses to the Questionnaires on Integrated Design

In this Appendix responses and comments are examined and analyzed for the 7 questions of the first questionnaire, to the 4 questions of the second questionnaire and finally to additional issues raised by the RAE.

1. First questionnaire

Question 1: IN YOUR OPINION, IS DESIGN INTEGRATION

(a) a desirable

(b) meaningful and

(c) realizable

OBJECTIVE AND AT WHAT DESIGN LEVELS?

Answers: There is a general agreement that design integration is a desirable and meaningful objective at all design levels, but there are differing opinions concerning the realizability at the detailed design level, integration being an increasingly difficult task when advancing from conceptual to detailed design stage. Design integration is also qualified as essential, of great value and even mandatory for high performance vehicles. It is also noted, that instead of full automation the preferred solution consists in integrated databases, company-wide data banks, and considerable man-in-the loop involvement for decision-making.

Based on IPAD experience, an answer from NASA states that integration at all three design levels is definitely realizable using innovative formal task decomposition methods.

Question 2: IN WHAT RESPECT ARE ADVANCES IN AEROSPACE AND COMPUTER TECHNOLOGY BECOMING A DRIVING FORCE FOR DESIGN INTEGRATION?

Answers: As aerospace products are becoming more and more complex and increasingly removed from previous experience, reliance must be placed from the beginning on in-depth analysis and optimization. In addition, the general system concept philosophy,replacing the traditional marriage of aerodynamics, structures, propulsion and subsystems by an overall vehicle concept with its payload, mission and environment, makes design integration an almost direct outcome. Furthermore, the advent of intelligent systems, receiving messages from their own sensors, instead of a passive vehicle responding to human inputs, is itself a strong driver towards design integration.

On the computer side, in addition to technological advances with favorable cost reduction, design integration comes naturally as a consequence of software/hardware advances in data management and executive capabilities.

Question 3: WHAT ARE THE MOST IMPORTANT BENEFITS OF DESIGN INTEGRATION AT THE CONCEPTUAL, PRELIMINARY AND DETAILED DESIGN LEVEL?

Answers: At the conceptual and preliminary design stage the most important benefits are: reduction of iteration cycles in time and cost, quick assessment of the effects of specification changes and of new ideas, more in-depth studies and alternate options, better overall optimization and tradeoffs, bringing to the surface the synergistic effects of strongly interacting disciplines, giving a better balanced design and helping to understand the real issues, improved data transmission and communication, better access to design information, producing constructive dialogue between disciplines, and better use of human potential,

Additional benefits provided at the detailed design level include: improvement of accuracy and coherence through centralized databases, enhanced management visibility, helping in decision-making, smooth transition to manufacturing, increasing productivity, reduced cost, and relieving pressure to a too early design freeze

Question 4: WHAT ARE, IN YOUR OPINION, THE PROBLEM AREAS WHICH IN THE PAST PREVENTED THE DEVELOPMENT OF EFFICIENT INTEGRATED

Answers: There are many historical reasons including: fear of change, conservatism, difficulties to break traditional compartmentation; lack of adequate tools for fast computation, storage, communication interactivity and interfaces; high cost and low anticipated cost-effectiveness; lack of overall concepts how to carry out the whole system analysis and synthesis; lack of software standards; lack of available manpower and expertise to establish and maintain such programs; lack of sufficient management support; hardware compatibility problems; misconception of the restrictive identification of CAD with electronic drafting; computer sizing selection on the basis of individual disciplines; trend of large groups to be organized in separated disciplines; and fear that the benefits of specialists' expertise and judgment will be lost by computerization

Question 5: HOW WILL NEW COMPUTER CAPABILITIES ALLOW THE SOLUTION OF THESE PROBLEMS, IN PARTICULAR IN THE FOLLOWING AREAS:

(a) Data base collection

(b) Data base manipulation

(c) Data manipulation

(d) Interfacing between analysis, synthesis, drafting and manufacturing computer programs

(e) Interactivity

(d) Modularity and growth potential

(f) Computer system compatibility

Answers: New larger computers will clearly bring improvements in all these areas by: the increased information storage capability resulting from the mass memory growth; allowing manipulation and processing of larger amount of data by increased computer speed and CPU memory size; development of interfaces between design and manufacturing by enlarged information storage and improved telecommunication and teleprocessing systems (in particular in speed and number of lines); enhancement of interactivity and "user friendly" communication between operator and computer by "smart terminals" and extensive use of versatile graphic systems as color video, etc...; the flexibility obtained from hardware and software modularity and network structure; the expected relief of hardware compatibility problems as manufacturers are accepting international standards; developing software for relational data bases; transportability of programs using specifications for programming; using problem oriented pre-and post-processors to allow easy interfacing; and shifting emphasis from searching for high efficiency in programming to more general (perhaps less efficient) "software engineering" techniques, producing systems which can be maintained and developed easier.

As a result of these capabilities an integrated system development of many large programs will become as simple as writing today a Fortran program calling on many subroutines.

Question 6: WHAT ARE THE POSSIBLE HARDWARE AND SOFTWARE STRUCTURES FOR A FEASIBLE AND VERSATILE INTEGRATED DESIGN PROCESS?

Answers The choice between a centralized supercomputer and a decentralized or a distributed system appears difficult. However, there are definite requirements to be met by all candidate solutions: all participants in the design process must have an easy access to the common data base; communication between systems must be fast enough and able to deliver high dataflows; and standard modular software structure and language are essential.

The following solutions can be proposed:

(a) A centralized mainframe hardware and software with satellite system used only minimally. Basic operating practice would be to do all work on one or more centrally located and jointly linked large computers, ensuring that data base information is accurate and available when required.

(b) The concept of formal decomposition of a large design problem into many coordinated subproblems leads to a computer network implementation as a natural solution. Computers in such a network, matched and dedicated to the subproblem requirements, will operate concurrently to compress the design process in time.

(c) A powerful central computing system for management and exchange of data and for complex computing tasks, providing bulk CPU power, interconnected to local computers for distributed tasks.

It is noted also that the high level of sophistication and integration required in developing such systems is beyond the capability of a single company or even a research institution. A Consortium of organizations from NATO countries is suggested to share the skills and interests, and to develop, maintain and keep up-to-date computer programs. In addition a complete system could be fashioned either in the form of a single computer situated in a convenient location, serviced by people of the Consortium and connected to the associated member organizations through interactive terminals, or by a network of computers placed in different countries and each one connected through terminals to the associated companies of the area.

Question 7: POSSIBLE TIME SCHEDULES FOR THE IMPLEMENTATION OF INTEGRATED COMPUTER-AIDED DESIGN PROGRAMS AT VARIOUS DESIGN STAGES?

Answers: There is a qualitative agreement (at least) in the answers obtained. The average expected time schedule is the following:

Conceptual design: now, for leading companies

Preliminary design: mid-1980s for leading companies late 1980s for most others

Detailed design: late 1980s to mid-1990s

2. Second questionnaire

A limited number of responses was received to this second questionnaire and the main points are discussed as follows:

Question (a) IS OR WILL INTEGRATED DESIGN BE A HIGH PRIORITY ITEM IN THE VARIOUS ORGANIZATIONS?

Answers: It appears that this is the case, in most organizations, for conceptual and preliminary design; for detailed design it is or soon will be so. Integration of design tools is crucial to cost-effective structural design and an adequate interface with aerodynamics software systems is urgently required.

Question (b) CAN IMPLEMENTATION BE REALIZED ON A PROGRESSIVE BASIS OR AFTER DEVELOPMENT OF A TOTAL SYSTEM?

Answers: Both solutions are acceptable, but a "bottom up" progressive approach would be most effective within a coherent development program and a sound specification of the functional/data interfaces.

Question (c) IS THERE ANY COMPARABLE EFFORT FOR THE DATA BASE COLLECTION AND MANAGEMENT AND FOR EXECUTIVE PROGRAM DEVELOPMENT AS WAS PROVIDED IN RECENT YEARS FOR COMPUTER AIDED GRAPHICS?

Answers: There is such an effort in particular areas and design stages, except with the IPAD program which is a total system integration software applicable at all design stages.

Question (d) WHAT TYPES AND ARCHITECTURES OF COMPUTERS APPEAR PROMISING FOR COST-EFFECTIVE IMPLEMENTATION OF INTEGRATED DESIGN?

Answers: Front ending or networking for Class 6 computers; or large central mainframe for shared data management supported by distributed network of specialized computers.

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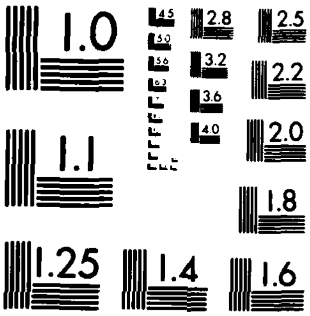

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3. Questions and comments from RAE and BAe

i) WHAT PROGRAMS COULD USEFULLY BE EXTENDED IF LIMITS ON COMPUTING CAPACITY WERE REMOVED?

The increased computing power would be used to speed up studies and hence allow more thorough investigations at earlier design stages, including at the conceptual level. More detailed aircraft modelling as for example in selection of aircraft-weapon-propulsion configurations, more advanced aerodynamic and structural analysis methods, presently too expensive and requiring too long computer times would be practicable. All finite element methods can benefit from the ability to handle larger numbers of elements. However realization of these studies would imply also an increased need of manpower with multidisciplinary expertise.

ii) WHAT PROGRAMS COULD BE JOINED TOGETHER ON AN INTERDISCIPLINARY BASIS?

Possible candidates are aerodynamic loading and derivatives, mass distribution, stress and flexibility analysis and structural optimization/redesign. If there is any remodelling of the problems between full cycle iterations, it is probably best handled by interactive intervention of designers and technical experts.

Another important large-scale application will be rotor aerodynamics coupled with aeroelastic deformations, vehicle vibrations, etc...

iii) WHAT NEW PROSPECTS ARE OPENED UP IF LARGE-SCALE COMPUTING FACILITIES BECOME AVAILABLE?

We are approaching the stage where all known basic calculation in relation to airframe design can be programmed. The problems will remain of understanding and formalizing the basic physics and of organizing thoughts in such a way that enormously large calculations can be managed. This must mean enclosing whole areas of knowledge into "expert systems" able to support a logically defined process of design. This will include "black box" elements providing specific solutions to well specified requirements to help the user to model problems accurately and guide him to better designs. The computing power does not make such systems feasible but provides promise to justify thinking in this direction.

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3. LARGE COMPUTING CAPABILITIES

3.1 Introduction

In the preceeding sections the computational capabilities required by the several disciplinary and interdisciplinary aeronautical users have been discussed in terms of two simple measures, namely speed and memory capacity. While conceptually valuable in defining applications requirements and sizing them relative to current marketplace offerings, such a simple characterization is not adequate as a statement of requirements and further factors are considered here. Thus, in establishing the scope of requirements for aeronautical research and development computing applications, the needs as defined by the questionnaire responses provide the basis for this analysis of capabilities and options. The information included for current and projected computing system capabilities comes from several sources including currently available systems and projections provided by the major computer manufacturers.

3.2 Computer Requirements

In addition to speed and memory capacity, three further factors are considered here as a more complete way of expressing computing requirements capability (operational characteristics; data base and input/output activity; and computational load). Responses to user questionnaires sent to a large number of organizations involved in aeronautical research and development provided the basis for this analysis of computer requirements. Those results are summarized as follows:

(a) Operational Characteristics

Users stressed the importance of graphic displays and other user-friendly features particularly when frequent interaction with the operator is required. Special security and proprietary data protection were recognized as necessary and, although catered for by public data networks to some degree, remain as unresolved issues in the design of any future decentralized system.

(b) Data Base and Input/Output

High rates of data transfer were identified as an important feature of most aeronautical applications; however, conventional access methods were generally regarded as adequate. Heaviest demands on input/output systems arise from graphics and simulation uses and may also arise in arrangements which attempt to link local equipment to a central facility.

(c) Computational Load

To some degree, the computational load can be reduced by advances in algorithmic and programming techniques and the use of special compilers; Fortran is used predominantly, with assembler language used in critical sections giving an increase in performance of 2 in scalar mode and up to 10 in vector mode. Program size did not appear as a major design factor and systems of up to 1000 subroutines comprising 1 Megabyte of main store resident instructions are adequate for most purposes. Addressable memory requirements varied widely with specific application, up to 10^{14} bits. Sustained rate of execution requirements also varied considerably up to 10^{10} flops (floating point operations per second). Future increases would probably demand both greater performance and more efficient algorithms. Both vector and matrix data structures appear prominently in most applications with special cases such as banded or triangular arrays occuring in fluid dynamics and structural analysis. Most computational problems are not easily compartmented into separate segments.

Existing commercially available computers include both serial procesors (Cyber 170, IBM 3081, Amdahl 470 V8) and vector processors (Cyber 205, Cray 1) generally termed Class 6 computers. Computers anticipated by 1985 include more powerful versions and derivatives of these systems (and in addition emerging Japanese equipment), which offer up to 200 million flops with up to 32 million byte memory size. Advanced US and Japanese computers, planned for operation by early 1990s will extend this capability to 1,000 million flops (Mflops) and 250 million bytes or more memory size, using newer technology and architecture.

Beyond 1990 it can be expected that advances in technology and architectural design will permit further improvements in size and speed of large central computers and central computing arrays, and potentially, of decentralized systems. While progress toward these latter systems is somewhat speculative at this time, one can expect that the systems software developments required to address the process control issues of decentralized systems will, in due time, be successfully treated by the computing community. Significant advantages can result from the successful resolution of these problems and the emergence of decentralized systems. Some are: modularity, giving architectural simplicity; parallel processing of independent program elements; and the ability to aggregate and bring to bear a more powerful computing capability on very large and infrequently encountered applications. These potential advantages are not without some implementation problems however, including hardware developments(e.g. synchronization), difficulty of adapting current algorithms, user acceptance resistance resulting from the major investment of effort required in program transformation to new systems, new language structures, etc. Nonetheless, these new developments will undoubtedly offer sufficient advantages in numerical simulation so as to offset the transformation difficulties. The user will accept and use them when they become economically attractive or imperative.

Currently in the research phase are architectural arrangements, such as the heterogeneous element processor (HEP), in which modular architecture is utilized in conjunction with a large number of the more advanced processors (e.g. 16xCray 1), linked to a similar number of memory banks via crossbar switching, giving an anticipated speed of 400 Mflops. The relative advantages of this approach compared with the conventional central system approach remain to be demonstrated.

The requirements for communications networks and their role in aggregating computers into broad geographical networks was considered and the importance recognized; however, no firm conclusions are drawn in this regard. Although such networks exist today(largely telephone communication networks) their value in the context of aeronautical research and development applications of very larger computers is currently severely restricted by bandwidth limitations. The rate at which communications technology will remove these limitations is not easily projected and the prospects for decentralized computer systems, comprising major assets at dispersed geographical locations, remain uncertain. The issue is discussed further in the next section on options.

3.3 Options for Large Computing Facility Capabilities

Access to large computing capabilities for AGARD members may be addressed within a framework ranging from a centralized supercomputer system, accessed by all members, to several decentralized systems which may or may not be accessible to other member nations. In any event, the combinations of accessibility must meet the needs of each member to be effective. Taken in this light there is a range of options which may be envisioned and which could be responsive to the requirements of the member nations. To set as a goal the immediate achievement of universal access to a "supercenter" capability would be not only quite expensive (perhaps prohibitively so) but also difficult because of the complexity of the system required and the learning process through which users must go to operate effectively. Rather, an evolutionary approach should be undertaken, working from current capabilities in place toward a continuing improvement of capability and user access and toward an ultimate system capability.

In this regard it is helpful to review computer system capabilities existing today and those which can be expected to appear in the marketplace in the next decade. In a paper presented earlier this year (January 1983) at an AIAA conference in the U.S., Dr. Paul Kutler of the NASA-Ames Research Center presented a summary of existing and proposed mainframe computers (*Table 1*).

Since these data were published it has become known that the CRAY 2 system will be available with 32M or maybe even 256M word memory, although at a somewhat later date than that indicated. NASA's NAS (Numerical Aerodynamic Simulator) should be viewed in a somewhat different context than this table implies. Current concepts for NAS envision a processing system network geographically centralized but logically separated into large computing engines, data storage facilities, support processing systems (front ends) and user working stations. The large computing engines are to comprise prototype versions of emerging large systems (CYBER 2XX, CRAY 2, etc.) aiming at the NAS goal of one billion floating point operations per second (1000 Mflops).

It is reasonable to expect that advanced system research and development efforts worldwide will result in the introduction of systems in the two to ten billion floating point operations per second range (2-10 giga flops) within the next ten years. Japanese computer manufacturers have in fact, through the Japanese Ministry of International Technology and Industry, established a 10 giga flop objective by the 1990s and have committed major financial resources to this effort.

In the context of the current aeronautical applications identified in earlier sections of this report, currently available Class 6 systems (Control Data Corp. CYBER 205 and Cray Research, Inc., CRAY 1S at 400 Mflops and 160 Mflops, respectively) are able to successfully respond to the computing speed requirements of numerical aerodynamic simulation based on inviscid with viscous correction formulations. The CRAY X-MP and 1M models, available in mid 1984, represent additional options to be considered. The Japanese firms of Fujitsü and Hitachi will be fielding machines in that same performance range by end of 1984. It is clear that adequate computing system hardware is available to respond to the requirements for the application of inviscid aerodynamics codes to current real world engineering problems in nonmaneuvering aircraft design.

The next level of applications for maneuvering aircraft design, in which viscous flow fields must be simulated using Navier Stokes codes, must await the next generation of supercomputer development. Similarly, high fidelity simulation of internal flows with rotating compressors and combustion will require this higher performance generation of computing engine. We would not expect to see this until around 1990.

Now returning to the needs of the NATO/AGARD user community there are clearly several levels of capability needed. Two are immediately apparent and can form the basis of a planning effort to achieve a proper system capability. On the one hand, there are the current users of large computers who are experienced in the development of aeronautical technology. Typically these are the major research laboratories, universities, and aerospace companies with on-going numerical simulation research and development programs. They will have in place large computer systems of the Class 6 level or approaching that level (50-100 million floating point operations per second) and will have developed significant libraries of aeronautical codes for flow simulation, structural design, propulsion systems design, etc. and will have moved in the direction of design integration and optimization code development. On the other hand, there are potential users not yet experienced in numerical simulation and who could profit greatly from assistance by the more advanced NATO/AGARD members. Under the auspices of AGARD, such assistance could allow other members to advance more rapidly toward technological, and thus economic, maturity.

Inherent in this line of thought is the establishment of a capabilities- sharing concept. It is unlikely that any member would readily make available the totality of his capability in aeronautical design since he would thereby forefeit his military or commercial competitive advantage. On the other hand, there may well be a significant range of capabilities which lie in the "open literature" and/or which are no longer critical to the competitive advantage of that member. He might then be willing to make them available to less advanced members under some business arrangement which could contribute importantly to their advancement. Sharing existing capabilities through an AGARD sponsored arrangement is clearly a key concept in moving ahead quickly and effectively. Either direct arrangements between the advanced and not so advanced members to share access to computing capability and existing codes, or a scheme of centralizing to some degree the hardware and software code capabilities to provide for training and development of developing users, should be envisioned.

Assuming for a moment a willingness on the part of the more advanced entities (in aeronautical computer applications) in several member nations to share a selected portion of their computing codes, and to allow access to some computing resource on which those codes could be executed, one can envision a primitive resource sharing network as shown in Figure 1.

Achievement of this level of cooperative computing resource sharing is quite straightforward from a hardware system standpoint. Three elements are required: first, the willingness to share certain applications codes, and the computing machine access to execute them; secondly, a terminal capability (which may be either elementary or advanced) at the user sites; and finally, in-place commercial dial-up telephone services to link users to resources on an as needed basis. No extensive network system need be developed, the resources exist and terminal equipment is not a major expense. The key issues here are the willingness to share resources and the ability to gainfully utilise them. These issues are non-trivial! They will require the most careful analysis and review and may turn upon policy judgements of government and corporate management because they involve pioneering steps in exposure to external access of previously carefully protected private data bases and a commitment to training assistance to unsophisticated computer users.

Successful achievement of this primitive level of computer networking would nonetheless comprise an important step in aggregate resource utilization among NATO/AGARD member nations and, while not essential to a second level of development, would establish an important basis for that further development. Appropriate training could thus begin at each user nation, an appreciation for the technological impact of computer simulations would be established, and the "culture" of high technology would be enormously enhanced.

Closely associated with this level of cooperative resource sharing should be the establishment of communal functions aimed at achieving objectives not readily gained by resource sharing. Reference is made here to advanced training and education in numerical simulation and the development of common libraries of basic codes, utilities and algorithms which are basic to establishment of a major numerical simulation capability. An existing University or Center, having established objectives of education and training in aeronautical technology, would be an appropriate communal facility for enhancing the development of numerical simulation applications in aeronautical technology. Such a University or Center would provide ready and accelerated access to the aggregated knowledge in the field of numerical simulation by scientific participants from the user countries. It could thus enable them to "leap-frog" the halting, and sometimes tedious research process that has preceeded current state-of-the-art in this field.

Given the establishment of such a communal facility, the basis would then exist for the evolutionary development of a communication network connecting with other existing computing facilities among the member nations. In this regard it is worth mentioning that ARPANET, a network currently based to connect computing facilities for research purposes, is being absorbed into the Defence Data Network (DDN) and that DDN will in the future provide both secure and non-secure communications links between the U.S. and Europe. Thus, it is conceivable that DDN may be able to offer the means of connecting computer facilitiers across the Atlantic.

The objective of advancing the science of numerical simulation through exchange of scientific information could thus be achieved as a result of better communication. The goal of these efforts should be the continued development of a mutually accessible computational resource combining the centralized system, a transparent data communication network, and the work station/graphic station capabilities located at the various user nodes of the network. Additionally one would expect that the capabilities of the various nodes would be continually improved in the interest of developing a degree of independence from the communal node. In Figure 2 an intermediate stage of the development of such a network is indicated. Here "Resource B" would be the centralized facility and the wide bandwidth communication channels (indicated by the heavy lines) would begin to emerge between nodes where the data communication requirements warranted. The dial-up links would be enhanced as telephone system technology permits and as need demands.

Implementation of such a jointly sponsored facility requires two initial steps. First must be a collective decision to proceed; the mechanics of the computational system are not complex, but the decision process may be difficult and may require the creation of a "Board of Governors" assigned the task of establishing the overall objectives and policies of the communal facility. The second step is the creation of a communal node, as described in the previous discussion, to be undertaken by an operating organization responsive to the Board of Governors.

Having set down the essential message of this section, it is of value to review the considerations which lead to this introductory statement. At least two broad concepts have been put forth in discussions relating to the provision of large computing power to the NATO/AGARD community. On the one hand the concept of a very large "super center" with the most advanced computing equipment accessed and shared by all members, has been considered. In the US, NASA has, in fact, embarked upon this avenue and has initiated the development of a large computing system to be installed at the Ames Research Center in California. Its announced objective is to "develop a unique large-scale, high-performance, computational resource for solving viscous, three-dimensional, fluid-flow equations specially oriented toward the solution of aerodynamic and fluid dynamic problems." The NASA approach is to acquire each new computer system offering at the prototype stage as it is developed. In so doing they will be assured of the most powerful computing equipments available at any given time and, given the prototype aspect of the plan, will be at the leading edge of computing capability. The premise here is that the science of numerical simulation in aeronautical technology (and in the broader field of physical processes in which they are also committed to do research) will be more rapidly advanced when the researchers have the most powerful computing tools at their service. That concept should be borne in mind in analyzing the AGARD requirements since the AGARD's objective may well differ from that of NASA.

On the other hand much thought has been given to the idea that, through a combination of resources located at the various member laboratories within the NATO/AGARD community, an aggregate "super computing" capability could be achieved. This distributed capability concept is one that has long intrigued the computer science community and, in theory, has considerable merit. It rests on the premise that computing applications can be segmented and allocated to various computing engines, either specialized or not, at the distributed locations and that the segmented solutions can then be recombined into the total problem solution. In fact, incorporated into the NASA strategy for large computing usage at its aeronautical research centers is an element of this distributed resource sharing concept. In their analysis the distributed capability aspect rests most strongly on the differentiation of missions among the various aeronautical laboratories (Ames, Langley, Lewis) and the objective of combining those capabilities in some synergistic way for the common good of the scientific objective. Envisioned here is the remote access by a researcher to a developmental research code provided by a colleague at another laboratory. Having established code compatibility it is expected that the developmental code would then be transported to his home site (and computer) and used locally in the furtherance of the research effort. This is an important distinction in distributed capability where the scientific developments are the shared objective, rather the computing capability itself.

The difficulty (current inability) to manage a distributed computing capability in attacking a single large application is recognized in this strategy. Several obstacles are currently interposed to the distributed system objective and, pending their resolution, effectively prohibit such an implementation. Probably most important at this point is the unavailability of reliable wide-band communications networks which would enable the transfer of the large data bases necessary to large numerical simulation applications. Typically, working memories of 10 to 50 million words are required for the "disturbed" aerodynamic flow field definition. To achieve effective utilization of distributed processors on that kind of problem requires the transfer and frequent update of the data base and thus a very large data communication requirement. Even a relatively small 10 million word data base (3/4 billion bits), transferred on the scale of seconds necessary for effective utilization of large computers, would require 500 times the currently available 50 kilobit data communication systems. Satellite communication nets will certainly increase that capability shortly and must be borne in mind in the overall system concept and evolution. It must also be remembered that the communication network is only one element of the data communication system and that the overhead times introduced by other elements of the system seriously degrade the effective line bandwidth capability of the network.

There is, however, a second difficulty not yet resolved by the computer system designers, although much effort is being expended on it and one would reasonably expect a solution to be introduced into the computer equipment market-place (for super computers at least) by the end of this decade. That is the ability to segment a single large problem to run effectively on several separate processing elements which are at best loosely coupled and at worst (in the case of distributed networks) uncoupled. Problem segmentation, resynchronization, working data base updates and coordination, are very difficult issues which must be overcome. In the case of widely distributed systems an added factor of non-uniform hardware introduces a third difficulty which is not being addressed by the computer manufacturing community. It is at present an issue for academic study. An added complicating factor is that distributed (thus decentralized) computers are under the control of the various centers owners and managers. Coordinated scheduling of numerous resources, given the various priorities of each center, is very tedious and a significant obstacle to effective performance on large multi-center applications.

The objective of this discussion is not to say that the concept of distributed systems cannot be brought into being. Rather it is to suggest that there are significant obstacles to implementation of the concept and to recognise that other approaches must be taken into account. In all likelihood the appropriate approach will incorporate elements of both concepts and should follow an evolutionary development path. Management of such a "hybrid" system of associated resources will require some centralisation simply from the standpoint of consistency in the charging algorithms and a "clearing house" to provide information on the availability of various system resources. As a second evolutionary step the "clearing house" should consider undertaking the responsibility for charges on the various resources in the network. Analysis of the needs of the NATO/AGARD community and the definition of directions for future development represents further steps toward centralised management of the system. It would seem appropriate for the central node to be the one taking these steps in response to the Governing Board.

In the overview one might expect the evolution to follow along the lines outlined below. The starting point is, of course, the current status of computing resources in the community, consisting of computing systems at various company, university, and government laboratories and the libraries of codes existing in those installations.

Stage 1. Each member moves ahead unilaterally but with some recognition of the joint objectives of the NATO/AGARD community to ultimately join in some common-benefit computing activity. The moves here would range from the acquisition of a large (Class 6-like) system, justified on the basis of their own needs, to arrangements between the Southern Flank members and other members for access to selected codes and computing resources.

Stage 2. The development and establishment of the communal node and the development of a plan of action for that node. That plan should incorporate the training and development of the interested Southern Flank members in the utilization of large computing resources in aeronautics. It should also focus on the analysis of the requirements of the communal node, recognizing the geographically decentralized nature of the NATO/AGARD community and their desire for autonomy, and on the advocacy of a program to establish computing system capabilities at the communal node. The establishment of a governing body of user member representatives is essential to this stage.

Stage 3. The implementation of a system capability at the communal node. It should comprise those capabilities which are not judged economically justifiable by the individual members because of the major capital outlays required, but which are recognized as mutually desirable by the members to the extent that they are willing to support the system on a subscription share basis. Essential here also is the establishment of an adequate data communication system utilizing, to the maximum degree possible, the common carrier capabilities of the community.

Stage 4. The continuing evolution and management of the communal node system under the direction of the governing body of user member representatives. This stage represents the long term operation of the system.

The development of the communal node would certainly be a key element in the evolution of a NATO system network. While the acquisition of a large computing capability of the Class 6, or larger, scale will be viewed as desirable the cost of such an acquisition will require extensive review and a lengthy decision process. On the other hand, the establishment of the training role should be much more readily accomplished. Assuming for the moment that this is the case, the establishment of an appropriate library of aerodynamic codes, the establishment of a curriculum for training representatives of the member nations, and the utilization and upgrading of the computing facilities at the communal node should be the initial activities and should be pursued with vigor. In that light the current offerings in the supercomputer marketplace do, in fact, represent a significant advancement in capability for at least the large majority of NATO members. The CYBER 205 and Cray XMP systems comprise the most powerful systems currently offered and should be viewed as the near term objective of both the communal node and individual members who have the basis for an acquisition of that scale. An outlay of $10 to $20 millions (for purchase of a system) would be necessary depending on the complexity of the initial system and the buyers success in negotiating a favorable price. Real memory of up to 8 million words is available with the CYBER 205 system and both manufacturers offer large solid state backing store devices which enormously enhance the capability of the systems. Experience indicates that the large real memories tend to yield systems with much higher user satisfaction and productivity although virtual operating systems are able to manage extended storage with very little user intervention and minimum impact on the performance of the system. Excellent internal communications facilities are available with both systems so that early developmental focus should be on the engineer/scientist work stations and graphics display capabilities.

It is likewise important not to lose sight of the requirements for the continuing development and strengthening of the peripheral devices that surround the computing engine and give the users effective access to the system. The most important of these may well be the graphic display capabilities which enable the engineer/scientist to visualize both the problem input phase and the computational results analysis. These are becoming very much more important requirements as advancements are made in configuration description, grid generation, and flow field solution. The volumes of data generated by a large numerical simulation effectively defy interpretation without some automated assistance in visualization. The communal node may well appropriately take the lead in developing high quality peripheral devices for the member community. That is a common requirement of all members of the user community and one which could be for the common good.

A factor of major importance and concern to the potential user of this communal node facility is security of his private data sets, both those stored at the facility and those which are transmitted over common carrier facilities. Industrial secrets are an important element of successful competition between companies and countries and concern over their security will not be easily allayed. NASA has addressed this item in design of the Numerical Aerodynamic Simulation Facility from the standpoint of building adequate security measures into the data storage and the handling protocols of the system design. A system of software keys and passwords managed in the manner of hardware keys and locks by a security officer is the central theme of the approach. While such a system can be theoretically shown to have equivalent obstacles to unauthorized access as a physical security system, the fact that the data is not under the physical control of the owner in his own facility, coupled with the recurring reports of unauthorized access to bank accounts, payroll accounts, etc., does nothing to calm concerns about it. Nonetheless the use of computing systems is essential to modern technology and these issues are being successfully addressed in many areas. There is no basis to think that they cannot be successfully addressed in the present context.

3.4 General Remarks

Responding to the multifaceted needs of the NATO aeronautical community is a complex task, not simply because of the complexity of the application itself but also because of the individuality of the members. A Board of Governors would provide a guiding mechanism to analyze and define those needs and to develop the means to respond to the specific requirements as they evolve. Certainly, the individual members will develop their own computing capabilities consistent with their own needs and financial abilities. The common node then will be left with the responsibility for "filling the gaps" in capabilities left by those independent decisions and for meeting the unfilled needs of the members with lesser capabilities. In the final analysis the available aggregate computing resource must be responsive to the collective requirements of the members, be they in a network or not. Clearly, the capability of system hardware and software which is now available, and projected to be available in the next 5 years, can provide for a major advance over the systems now in use in the aeronautical engineering and development community. Communications capability and the ability to aggregate usage demand through some commonly supported facility can be major factors in promoting the acceptance of numerical techniques in the engineering community. There appears to be no question of the future value of computer applications, the issue is how to get there! Success of this common node endeavor will depend heavily on the ability of a Board of Governors to formulate policies to the satisfaction of the participants.

Table 1

Existing and proposed mainframe computing engine characteristics

PROCESSOR	CLOCK CYCLE nsec (10^{-9}) sec	MAIN MEMORY SIZE (megabytes/64 bit megawords)	SECONDARY MEMORY SIZE	MAXIMUM/ SUSTAINED VECTOR RATE mflops	NO. OF PROCESSORS	NO. OF PIPELINES	DATE AVAILABLE
CDC 7600	27.5	0.45 mb/0.06 mw	4 mb/0.5 mw	12/4	1	1	CURRENTLY
ILLIAC IV	80.0	1 mb/0.13 mw	96 mb/12 mw	**/35	64		EXTINCT
CRAY 1	12.5	32 mb/4 mw	256 mb/32 mw	160/45	1	1	CURRENTLY
CRAY X-MP	9.5	32 mb/4 mw	256 mb/32 mw	470/100	2	1 x 2	2ND Q '83
CRAY 2	4-6	**	**	2000/400	4	**	4TH Q '83
CYBER 205	20.0	64 mb/8 mw	256 mb/32 mw	400/80	1	4	CURRENTLY
CYBER 2XXX*	8	256 mb/32 mw	2048 mb/256 mw	2000/1000	2-4	8/PROCESSOR	3RD Q '85
FUJITSU VP200	15	256 mb/32 mw	NONE	500/**	1	4+	4TH Q '83
HITACHI S-810-20	**	256 mb/32 mw	**	630/**	**	**	4TH Q '83
NAS GOAL	?	256 mb/32 mw	2048 mb/256 mw	?/1000	?	?	'88

* SYSTEM SPECIFICATIONS ARE RELATED TO NAS FLOW MODEL PROCESSOR STUDIES

** INFORMATION NOT AVAILABLE

\+ 2 PIPELINES CLOCKED AT 7.5 ns GIVING THE EFFECT OF 4.

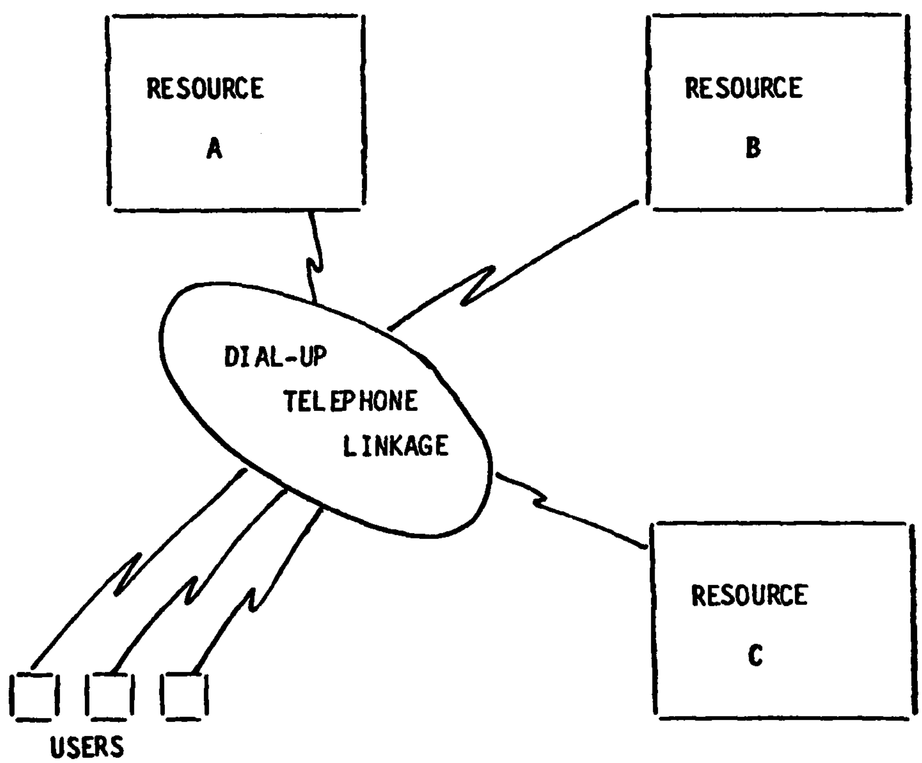

Figure 1 Existing resource sharing via dial-up low speed telephone lines

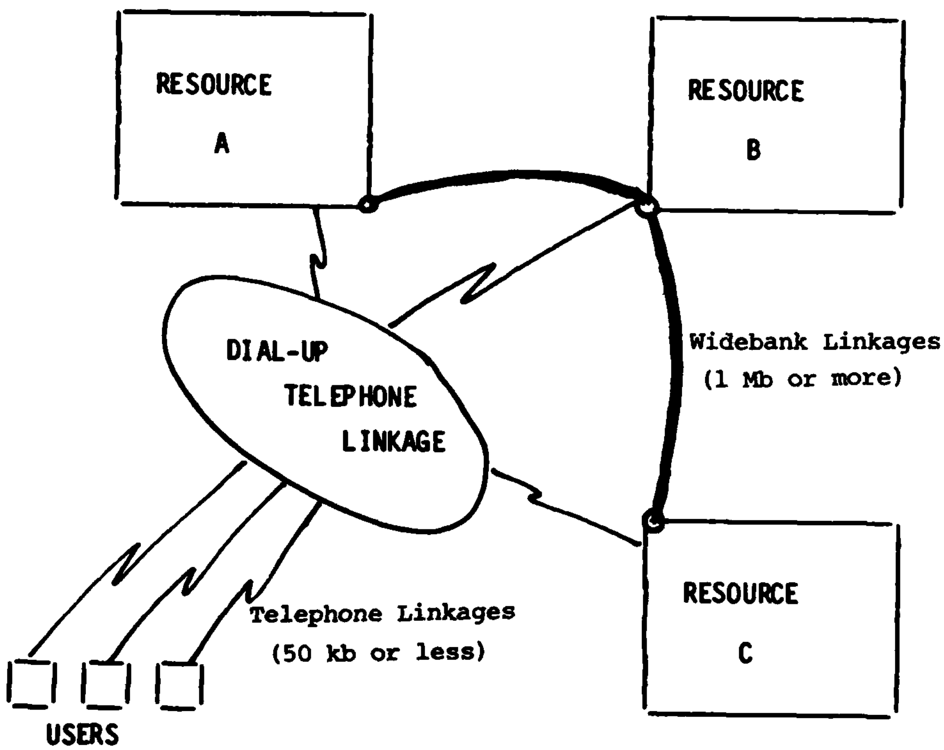

Figure 2 Intermediate level resource sharing utilizing both communal node (B) and distributed computing resources.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Recognising the general development of scientific supercomputers anticipated during the next decade and the resulting significant benefits to aeronautical research and development, the following conclusions are drawn with respect to the aeronautical uses of large computers:

1. Computer developments, eg the improvement of Class 6 computers anticipated by the mid 1980s and a potential further generation by the 1990s, will satisfy many of the disciplinary design research needs in aerodynamics, structures and materials, propulsion and flight mechanics.

2. The more demanding needs, for example, the accurate numerical simulation of highly separated flows over maneuvering aircraft, the advanced design of engines (involving internal aerodynamics, combustion, composite materials and structural dynamics) and special applications in flight dynamics such as the complete real-time simulation of rotorcraft, will not be met in the 1980s although current computer industry goals for the 1990s hold promise for such applications.

3. As an aid to interdisciplinary research and integrated design, the computer is expected to play an increasingly important role, as computer speed and capacity are increased to the point where various disciplinary, mission and cost modules can be accommodated.

4. Many of the ultimate needs of interdisciplinary research and integrated aerospace design, including full optimization of aircraft and engine configurations, will require substantial improvements in computer hardware and software beyond those anticipated in the 1980s and 1990s.

The computer needs of the aeronautical community are not sufficiently different from those of other scientific and engineering endeavors (eg weather analysis, petroleum exploration, biochemistry etc) to warrant the development of computers solely for aeronautical research. Within the context of a natural evolution of computing capabilities in response to a broad need of the science and engineering community, the following conclusions are drawn:

5. By 1990 it is envisaged that most major NATO Nations will have acquired very powerful computers for aeronautical research and development. However, there may be substantial merit in having, additionally, a centrally located facility that would permit all AGARD/NATO member countries to acquire knowledge, operating experience and specialized software which could be transferred to the individual member nations. Such a facility, would be of special benefit to the Southern Flank nations and to other NATO nations with emerging needs in aeronautics.

6. The linking of NATO member nation computing centers in a network, with a centrally located computing facility, appears attractive as a means of creating a shared super-capability. However the technical difficulties, data security issues, management complications and the costs of such an arrangement require careful examination.

4.2 Recommendations

Recognizing the widely differing levels of development in the use of large computers within NATO community, and recognizing the benefits that will result from ready access to modern computing facilities it seems clear that NATO/AGARD, as a general policy, should encourage cooperative technical exchanges among member nations with a view to upgrading and broadening the application of large scale computers to aeronautics. Within this context the following recommendations are made:

1. It is recommended that NATO/AGARD consider establishing a computer center accessible to all member nations, for the purpose of education, training, research directed toward the use of large computers in aeronautical applications, and as a library for shared data and computer codes. This center would also carry out a "path finder" function with an appropriately sized computing system and would provide for early usage by member nations pending acquisition of their own systems.

2. It is recommended that a limited capability data communication network among member nations be encouraged utilising currently available communication systems, thereby permitting remote access to this computer center by member nations. Such a network would be a precursor to a NATO-net.

3. It is recommended that NATO/AGARD commission a system study to define the issues involved in networking large computers of all member nations as a means to facilitate computer resource sharing, taking particular account of the security issue regarding proprietary data. Such a study would necessarily involve expertise in computer system architecture and data communication systems.

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28/29 October 1981 Church House, London, UK
11/12 May 1982 Church House, London, UK
6/7 October 1982 ONERA, Châtillon, France
7/8 April 1983 Church House, London, UK

Dq 105

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-AR-209	ISBN 92-835-1474-2	UNCLASSIFIED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title

LARGE SCALE COMPUTING IN AERONAUTICS

7. Presented at

8. Author(s)/Editor(s)	9. Date
Various	June 1984
10. Author's/Editor's Address	**11. Pages**
Various	110

12. Distribution Statement This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Computers
Data processing
Computer networks
NATO
Aeronautics
Aerodynamics
Military aircraft
Aircraft engines
Flight characteristics

14. Abstract

The current status, future needs and directions of large scale computing in aeronautics are reviewed with emphasis on fluid dynamics, structures and materials, propulsion and energetics, flight dynamics and integrated design. Computer applications in these disciplines are identified and the developments in computer capabilities anticipated for the 1980s and 1990s are discussed and summarized. Alternative means of providing access to computing facilities to NATO nations are considered including the provision of a central computing facility and the establishment of a computer network linking the NATO nations. It is concluded that currently available large computers will satisfy many of the disciplinary needs in the areas considered: that computers will play an increasingly important role in interdisciplinary research and integrated design: that such applications as the design of maneuvering aircraft, rotorcraft design and simulation, and advanced engine design, will place greater demands on computer capacity and speed than can be met during the next decade. Recommendations are made relating to the establishment of a NATO computer center and a NATO computer network that would permit members ready access for the purpose of training and early operating experience, and would provide a shared capability larger than that of many individual nations. The Working Group comprised representatives of four AGARD Panels (Fluid Dynamics Panel, Structures and Materials Panel, Propulsion and Energetics Panel, and Flight Mechanics Panel.)

This Advisory Report was prepared at the request of the Fluid Dynamics Panel of AGARD.

AGARD Advisory Report No.209
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ISBN 92-835-1474-2

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Government Reports Announcements (GRA)
published by the National Technical
Information Services, Springfield
Virginia 22161, USA

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

ISBN 92-835-1474-2

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