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NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

RTO LECTURE SERIES 211

Integrated Multidisciplinary Design of High Pressure Multistage Compressor Systems

(la Conception intégrée des compresseurs multi-étage à haute performance)

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Applied Vehicle Technology Panel and the Consultant and Exchange Programme of RTO presented on 14-15 September 1998 in Lyon, France, on 17-18 September 1998 in Cologne, Germany, and on 22-23 September 1998 in Cleveland, USA.

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- AVT Applied Vehicle Technology
- HFM Human Factors and Medicine

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Integrated Multidisciplinary Design of High Pressure Multistage Compressor Systems

(RTO EN-1)

Executive Summary

Today's aircraft gas turbine engines have remarkable performance characteristics. They provide thrust and avoid flame-out during the most demanding manoeuvres. There is also, amongst other attributes, a permanent improvement in fuel economy. Future aircraft will exceed by far today's performance envelopes.

These improvements have been made possible principally due to compressor performance. This Lecture Series covers the recent advances in the process of performing integrated design of high performance multistage compressors.

The purpose is to broaden the compressor designer's understanding beyond traditional fluid dynamics and to include the multidisciplinary systems approach required by modern gas turbine engines for longer life, lower acquisition and maintenance costs.

The design process requires an optimization of the entire machine, which may be significantly different from the best aerodynamic design of each stage or blade row. In addition, many modern engines are simultaneously increasing compressor performance, and reducing machine length, which reinforces the fluid and structure interactions. Finally, in order to reduce both production and maintenance costs, manufacturing constraints have to be taken into account in the initial phase of the design process.

The Lecture Series will underline the role of computational fluid dynamics, as well as solid mechanics and vibration simulations. The need for compressor designs to consider and model mechanical interactions and manufacturing concerns will be a central focus.

Keeping engine development ongoing and joining forces with the Nations is of utmost importance because tomorrow's engines can no longer be developed with today's simulation tools. It must also be seen that present reductions in research oriented budgets endanger the further development. This is another reason for bringing the latest state of the art information to the development engineers of as many NATO Nations as possible and to give them a forum for exchange and discussion, enabling them to further the development with coordinated forces.

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Applied Vehicle Technology Panel and the Consultant and Exchange Programme of RTO presented on 14-15 September 1998 in Lyon, France, on 17-18 September 1998 in Cologne, Germany, and on 22-23 September 1998 in Cleveland, USA.

La conception intégrée des compresseurs multi-étage à haute performance
(RTO-EN-1)

Synthèse

Les turbomoteurs modernes ont des caractéristiques de performance remarquables. Ils fournissent la poussée nécessaire et évitent l'extinction du réacteur même pendant les manoeuvres les plus difficiles. Parmi d'autres qualités, ils permettent de faire des économies durables au niveau de la consommation du carburant. Les enveloppes de performances d'aujourd'hui seront largement dépassées par les avions de combat de demain.

Ces améliorations sont principalement dues aux performances des compresseurs. Ce cycle de conférences couvre les avancées récentes dans le domaine de la conception intégrée de compresseurs multi-étage à hautes performances.

La conférence a pour objectif de permettre aux concepteurs de compresseurs d'élargir leurs connaissances, traditionnellement axées sur la dynamique des fluides, vers les systèmes pluridisciplinaires dans le but d'augmenter la durée de vie des turbomoteurs modernes et de diminuer les coûts d'acquisition et de maintenance.

Cette méthode de conception, qui exige d'optimiser intégralement le propulseur peut s'avérer tout à fait différente de l'optimisation aérodynamique de chaque étage ou de chaque grille d'aubes. En outre, pour de nombreux moteurs modernes, l'accroissement des performances en matière de compression va de pair avec une diminution de la taille, ce qui a pour effet d'améliorer les interactions entre le fluide et la structure. Enfin, il faut également tenir compte des contraintes de fabrication lors de la phase initiale de conception, afin de réduire les coûts de production et de maintenance.

Ce cycle de conférences soulignera le rôle de l'aérodynamique numérique dans ce processus, ainsi que celui de la mécanique des solides et de la simulation des vibrations. La prise en compte et la modélisation des interactions mécaniques, ainsi que les aspects industriels, constitueront le thème central de la conférence.

Il est d'une importance capitale de maintenir les activités de développement des moteurs d'avion en rassemblant les efforts des différents pays de l'OTAN, car il n'est plus envisageable de développer les moteurs de demain avec les moyens de simulation d'aujourd'hui. Cependant, les diminutions actuelles des budgets de recherche risquent de compromettre ces activités. Pour toutes ces raisons, il est important de mettre les dernières connaissances techniques à la disposition des ingénieurs concepteurs du plus grand nombre des pays de l'OTAN, et de leur offrir un forum pour des discussions et des échanges, leur permettant de coordonner et de faire avancer leur travaux de développement.

Les textes contenus dans cette publication ont été présentés lors d'un cycle de conférences organisé par la commission RTO des technologies appliquées aux véhicules, sous l'égide du programme des consultants et des échanges, du 14 au 15 septembre 1998 à Lyon en France, du 17 au 18 septembre 1998 à Cologne en Allemagne, et du 22 au 23 septembre 1998 à Cleveland aux Etats-Unis.

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INTEGRATED DESIGN OF HIGH PRESSURE MULTISTAGE ENGINE SYSTEMES

AN OVERVIEW

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1. SUMMARY

The gas turbine design associates very different engineering sciences, including aerodynamic, combustion, structure and mechanical systems, materials. Engines operate close to their limits of mechanical stability, with the help of electronic control systems. Extensive uses of simulation tools have enabled impressive improvements of performance and reliability.
Simultaneously, the designers put now their efforts on the global reduction of costs, such as the development and production costs, the maintenance, repair and disposal costs. The present design approach must include the concept of affordability of technological and financial resources.

2. INTRODUCTION

2.1 The global context

Two important constraints strongly influenced the design of a new motor: the global reduction of resources available for the development of new engines and the environmental concerns impose new limits on the noise and combustion emissions. Civil engines have taken into account this last constraint for a long time already, but military engines must also consider it, particularly for training operations during peace time.
As a consequence of the global reduction of resources available for the development of new engines, the affordability concept is a central concern of the designer. It includes the research and development costs, and it must include the maintenance aspect of the life cycle cost. The objective is not to realized the best machine with the best mechanical performances, such as the efficiency, the thrust or the highest level of reliability; the customer needs also an economical machine that fulfills the desired objective of performance. The designer needs then to reduce the costs without decreasing the quality of the design.
Figure 1 to Figure 3 present three examples of modern military engines; their performances are summarized in Table 1. They all have in common a high level of performance, performed in the frame of an integrated design approach. These are twin-shaft turbofans, with a 3-stage LP compressor, a cooled single stage HP turbine, and a cooled single stage LP turbine.

2.2 A few figures

The price of individual engines ranges from 3 to 10 million dollars. The development cost of a new engine is of the order of $1 billion dollars, while a derivative engine requires half of this amount. KUNTZMANN (1996) has proposed an appropriated formula as
$\text{Cost} = 0.1^* K^* \sqrt{\text{Thrust}}$; in this expression, K=1 to 2 for a new engine and K=0.5 to 1 for a derivative engine; Thrust is expressed in kN and Cost in billion dollars. The product cycle ranges from 20 to 40 years for an engine family. The return time on investment is of the order of 10 years for a new engine.
For an airline, the direct operating cost (DOC) is an important qualification parameter. The engine dependent costs range from 35% to more than 40% of the DOC (HERTEL, ALBERS, 1995, WISLER, 1998). Again depending on the aircraft family, a 1% DOC reduction requires 10% to 17% lower engine weight, 10% lower engine price, 5% lower specific fuel consumption (SFC). An important part of the usability costs of an airplane is linked to unscheduled incidents. For example, flight delay or cancellation will induce an average cost of 70,000$ per incident. This amount is equivalent to the airline direct operating cost for two flights, or to 3% of the fuel annual costs for the airplane (WISLER, 1998). According to HOPPER (1998), the unscheduled maintenance costs correspond to ten times the capital outlay for a widebody aircraft, and 2 to 3 for a military aircraft. The removal of a significant part of an engine far from normal area may cost 500,000£. The unreliability costs are estimated to 1M£ per civil airplane per year. In a fast jet military fleet, 30% of the aircraft are not available at any one time.

3. METHODS TO FULFILL THE DESIGN OBJECTIVES

3.1 Global process of optimization

The designer must optimize each engine element from the point of view of the mechanical and thermal conditions.

Paper presented at the RTO AVT Lecture Series on "Integrated Multidisciplinary Design of High Pressure Multistage Compression Systems", held in Lyon, France, 14-15 September 1998; Cologne, Germany, 17-18 September 1998; Cleveland, USA, 22-23 September 1998, and published in RTO EN-1.

To fulfill the design objectives, it is necessary to validate every element with 3D aero-mechanical and structural simulations, because the specific fuel consumption and the engine thrust depend on the aerodynamic blade performance. The interactions between the solid stress in the blade material and the aerodynamic flow around the blades should be taken into account for a good estimate of the blade vibrations. However, the global design optimum of the machine is different from the local optima of each component. The elements of the engine influence obviously their immediate neighborhood; for example, the condition at the exit of the combustion chamber is linked to the entry of the HP turbine. The engine's elements also influence the whole machine. This is obvious if we consider the coupling of the compressor and the turbine on a common shaft. The interactions between the engine components increase also with the level of performance. For examples, the distortion of the air intake may strongly influence the surge in the compressor, the value of the clearance gap at the blade tip is a function of the temperature, and then of the global engine operation. The designer must also perform a full engine structural simulation (Figure 8).
Finally we must also consider the criteria at the level of the engine or the aircraft-engine system as a consequence of the interest put in the cost, in the reduced engine signature and the reliability problem. Two main classes of criteria interest the designer: the performance and the reduction cost.

3.1.1 The performance criteria

Two global performance criteria are first considered: the specific fuel consumption (SFC = ratio of fuel mass flow to the net thrust) and the specific thrust (net thrust per air mass flow). For a given optimum specific thrust, highest engine technology results in the smallest core and therefore the lightest engine, the lowest SFC and therefore the lowest fuel tank size and mass. Extensive use of modern simulation tools has led to a 30% SFC reduction during the last 30 years for the subsonic engines (Figure 4). Military engines are also concerns with optimized acceleration, deceleration behavior, and with reduced signatures or low observability (radar, infrared, noise).
The designer can also restrict the flight range to a specific class of operation or he can extend it to fulfill various needs. For instance, the EJ200 was developed for two very different missions: the air superiority, that uses a 'dry' mode (without post-combustion), and the supersonic interception, that needs a post-combustion. The air superiority implies a minimization of the fan pressure ratio FPR to minimize the SFC while the supersonic interception needs the maximum of FPR. (Figure 6, SCHAFFLER, LAUER, 1998).

3.1.2 Life Cycle Cost

The future of the advanced design depends on the ability to maintain a low level for the Life Cycle Cost (LCC). This means a reduction of all costs, including research and development costs, production costs, direct operation and support costs (DOC), and finally the disposal costs. At the research and development level, the objective is to limit the number of tests for a new motor. The designer will then use extensively the numerical simulations, in parallel with the frequent use of derivative engines or off-the-shelf elements.

The question arises which constraint has the main impact on the decrease of the costs. Concerning the operation costs of an aircraft, the engine's part is 35%, and the fuel consumption is of the order of 15% of the aircraft's costs that means 40% of the engine's part. The decrease of the SFC is then of prime importance. According to WISLER (1998), a decrease of 1% of the direct operation costs may result either from a 3.7% reduction of the SFC, a 17% reduction of the engine's weight, a 7% decrease of the engine's cost or a 18% decrease of the maintenance's cost. However, only a significant increase of the compressor and turbine efficiencies (1% to 5%) allow to obtain a 1% SFC reduction. A 1% increase of the efficiency means also a 10% reduction of the aerodynamic losses, during the whole period of the engine operation. This is because the current technology allows already to reach high values of efficiency in compressors and turbines.

The LCC decrease requires an increase of the reliability. The reliability concept is particularly important for the extended use of ETOPS (Extended range Twin OPerationS) allowing civil aircraft to fly with one engine during at least 3h. The fan and compressor airfoils are one of the three main causes of engine related cause of in-flight shut down or aborted take-off (WISLER, 1998), probably due to bird ingestion or fatigue failure.
Maintenance also strongly influenced the LCC; the designer must plane the operations of maintenance at the early stage of the design, with the help of numerical tools, as CATIA for instance (Figure 7).

Reducing the LCC means also a work on the engine architecture to reduce the engine complexity, the number of elements and then the weight. This is a key factor for the choice of advanced cycles that must not exceed the LCC of more conventional designs. Advanced cycles may then include various elements: contra-rotating shafts, a variable dilution HP compressor, the management of compressor discharge air for turbine cooling, a variable exhaust nozzle as in the EJ200 and F414, a variable stagger angle for the BP turbine stator. The inlet guide vane in front of the fan allows to fit a wide aerodynamic flight domain, while avoiding mechanical resonance for the fan. In a military engine, the fan works on a wide domain of rotation, ranging from 35% to 105% of the nominal speed. However, the elimination of the inlet guide vane reduces the weight of the engine. The designers of the EJ200 have obtained a LCC reduction of 2.4% because they suppress the IGV, and introduce an interduct bearing support between the HP and BP turbines (SCHAFFLER, LAUER, 1998).

With the concurrent engineering, the companies expect a reduction of the non recurrent costs by 30 to 40% (COBLEY et al., 1997). This allows also to reduce the component development leadtime: the first rotation of the new generation military engines occur less than 24 months after the first studies (HERTEMAN, 1998, SCHÄFFLER, 1998). The designers of the PW150 achieve the first engine run within a year from the program lunch and certification after 36 months, while the early PW100 models require 60 months (HOSKING et al., 1998)

3.2 The path to good designs

Three factors appear necessary for the success of modern engines (HERTEMAN, 1998, BURNES et al., 1998). A rigorous project management is necessary, extensively using program plans and allowing risk identifications. Collocated working groups must be created at the early stage of the design process. These groups include members of design teams, production teams, aftersales service, and engineering production support. Also, the engine and aircraft designers must work in strong connection. This enables to define properly the engine performance requirements in the frame of the aircraft missions.

The success of the engine design process requires two supporting actions: the production and maintenance process improvements, and the understanding and modeling of the physical and mechanical phenomena. Technological maturation programs enable to avoid major risks before the first run of the engine. Figure 4 and Figure 5 present typical results for the progress in SFC and noise reductions.

The new compressors will reach a loading factor of DH/U^2 of 0.5 to 0.6, (HERTEMAN, 1998), still keeping a good efficiency. This means an extensive use of 3D aerodynamic simulations with good turbulence models, taking also into account the phenomena induced by small scale geometrical objects as for example the tip clearance gap at the extremities of the blades, the buttons of variable stagger stator or the gas injection from the disk cavities (ESCURET et al., 1997). The designer will use unsteady aerodynamic simulations to properly couple the blade rows, to increase the aerodynamic efficiency, and to improve the prediction of the unstable regimes as the surge or the rotating stall. Transient 3D analysis of mechanical structures in combination with transient thermal analyses are also of prime importance to simulate the fatigue behavior taking into account the long term influence of small defects, the consequence of foreign objects' injection, or the engine behaviour under extreme load conditions.
The strong increase of the pressure ratio and then of the temperature in the downstream part of the compressor leads to choose Ni base powder alloy, and Ti alumnides. The objective is here to decrease the mass. The choice of possible materials also limits the maximum pressure ratio in modern engine, (Tmax<900K at the compressor exit in the EJ200). The engineers will use metallic matrix composite (SiC-Ti) in the future for inner rings; they will use the blisk architecture more often, a single structure that combines the blades and the disk and allows lighter design.

4. Conclusions

The performance and the reliability of modern machines are nowadays very high. The good designs depend strongly on two "high tech" issues : to develop efficient simulations of engine performance, and to introduce new high temperature and light weight material.
Without to neglect these factors of performance and reliability, the designers put their efforts presently on the global reduction of costs, such as the development and production costs, the maintenance, repair and disposal costs.
All this evolution does not correspond to a modification of a paradigm. The gas turbine is still the best way to power an aircraft for a velocity higher than 250m/s, with a good propulsion efficiency. The recent development, such as the high bypass ratio engines, have again improved the interest for the gas turbine by strongly reducing the SFC.

The present design approach has included in the central concern the concept of affordability of technological and financial resources. The objective is then still the " high-tech " but at an affordable " low cost ".

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	EuroJet EJ200	F414-GE-400	SNECMA M88-2
Thrust	90kN (20,000 lb.)	97kN (22,000 lb.)	75 kN (17,000 lb.) AB 50 kN (11,250 lb.) dry
AB SFC			1.8 kg/daN.h
Dry SFC			0.8kg/daN.h
Airflow			65 kg/s
TIT			1,850 K
Bypass ratio	0.4		0.3
Fan pressure ratio	4.2		3.5
Overall pressure ratio	25.6		
LP compressor	3-stage overhung fan without IGV	3-stage fan with inlet guide vanes	3-stage fan with inlet guide vanes
HP compressor	5-stage	7-stage	6-stage with variable vanes
Combustion chamber		Annular	Annular
Afterburner		Central v-ring	Radial
Nozzle	Variable exhaust converging diverging nozzle	Variable exhaust converging diverging nozzle	Convergent nozzle
Reference	Schäffler, Lauer (1998) Kurzke, Riegler (1998)	Burnes, Blottenberger Elliot (1998)	(by courtesy of SNECMA)

Table 1: Military engine characteristics

Figure 1: F414-GE-400 General Electric (BURNES, T., OTTENBERGER, D.BI, ELLIOTT, M., 1998)

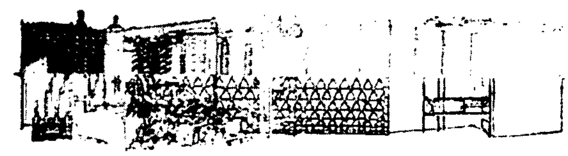

Figure 2: EJ200 EuroJet (GERSDORF, K.V., GRASMANN, K., SCHUBERT, H., 1996)

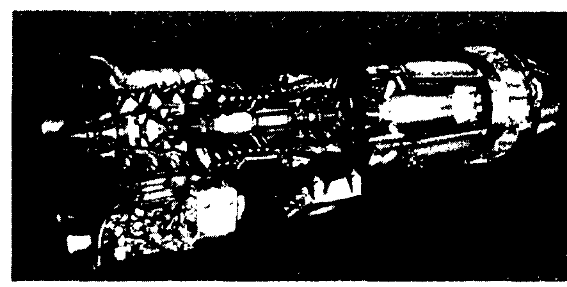

Figure 3: M88 Snecma (by courtesy of Snecma, 1998)

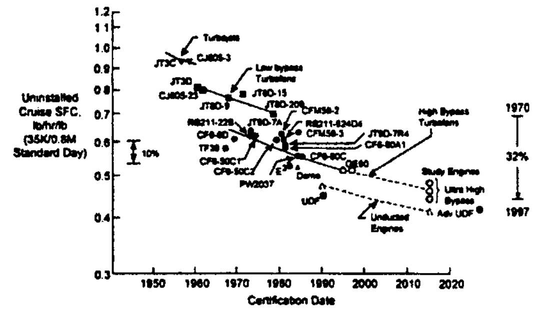

Figure 4: Trend of Specific Fuel Consumption for subsonic engines (Wisler, 1998)

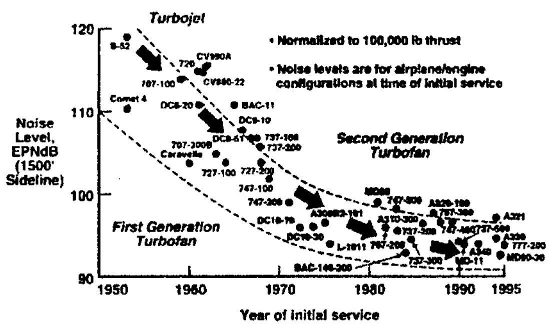

Figure 5: Noise reduction (STEPHENS, CAZIER, 1996)

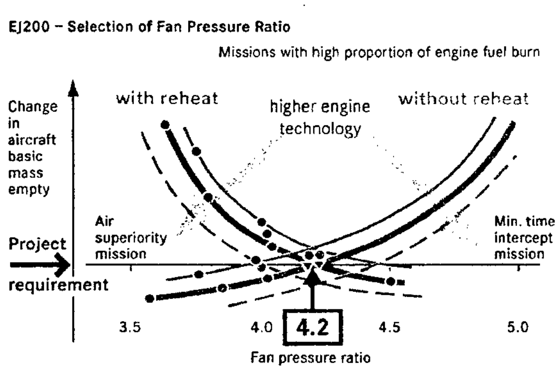

Figure 6: Selection of Fan pressure ratio in the EJ200 (Schäffler, Lauer, 1998)

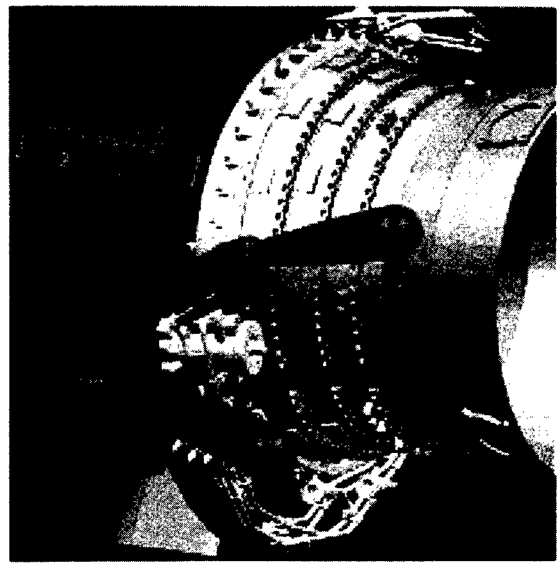

Figure 7: Verification of the access for the depose of a fuel pump in the CFM56-7 engine (Macheret, 1998)

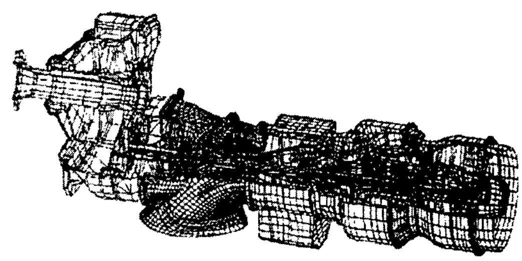

Figure 8: PW150 full engine finite element model (from HOSKING et al., 1998)

The Multidisciplinary Design Process

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1. SUMMARY

The complexity of the business process for multistage compressors is similar to that of complete aeroengines or propulsion systems and recent experience can be read across. Special attention is given to the description of the elements of the design process. Based on the necessity for a multidisciplinary approach a design team structure for simultaneous engineering is proposed. Some examples for typical tasks to be solved during the design process illustrate the advantage of an interactive multidisciplinary design and development.

2. INTRODUCTION

Today's multistage compressors are complex products of a highly specified industry. Modern blading technologies and aerodynamic design tools enable the achievement of excellent performance levels, mechanical and material technologies enable high reliabilities and low operating costs. It has been learnt that these improvements require a change in the design process aiming at an intensified dialogue between the involved technical disciplines. This is reflected by the introduction of simultaneous engineering, which directly improves the communication between the persons involved in the design and development process, but does not change any of the computational aids and their interfaces. Future projects will demand products with improved technology and improved quality, combined with drastically reduced design and development times. The competitiveness of companies will be bench marked by their ability to develop and deliver quality products demanded by the market in the shortest possible time. This can only be accomplished if the interaction and communication of all elements of the design process are improved further:

- human relations
- technology
- tools
- data structure

The current high technical standard has been achieved by the introduction of computational tools with continuously increasing accuracy and power, as well as the availability of accurate experimental techniques for validation of these tools. But most computational tools still reflect and support only one technical discipline as does the classical education of the engineers. Their core has been developed for sequential processes and the need to provide the final result for the next technical discipline. Improved interfaces at an earlier point in time were added artificially without a complete reengineering of the processes. For future demand, processes with a higher degree of parallel activities and with higher integration and interaction of individual disciplines have to be implemented, with extended technical responsibility of the individual specialists. This has to be supported by computational tools which operate from one single database ensuring full consistency of all data used in the design process /1/.

Modern multistage compressors are already the result of a highly complex design process, based on the engineers' broad experience, supported by numerous computational aids and still finally developed and optimised by various tests. This time consuming experimental development and verification is required as the complex interactions of all technologies and the global optimisation can not be formulated satisfactorily yet. While in each technical discipline high technological standards have been achieved - and will be improved further, the integration of the interactions of classical disciplines as design, aerodynamics, structures and vibrations into one single computational prediction method, e.g. the CAD tool is still extremely inadequate. Future technology acquisition programs have to ensure the development of new methods which reflect these challenges. This simple statement demands a total change of the way computational results are used. Currently different groups work in parallel on the same parts and their activities are linked at few milestones. Improvements are made by

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iterations through all disciplines. In future there will be one central data system providing consistent data, including the recent results and improvements, simultaneously to all areas. Iterations will be done much faster or even be substituted by computational optimisations.

The described changes will mainly effect the way engineering is working. The engineering process is one important part of the overall *product definition lifecycle*.

3. THE PRODUCT DEFINITION LIFECYCLE

Business world has changed from a technology driven approach to today's shareholder value orientated view. Company processes have been analyzed and changed to ensure that all activities are customer oriented and are run in the most efficient way. Analyses of customer to supplier relations have been extended from the pure external customer - supplier relation to the internal processes and their customer - supplier interfaces. With the emphasis on the total company shareholder value many companies introduced internal profit centers to ensure best value for money.

The overall process of the compressor design lifecycle does not differ from the processes used for the definition and marketing of complete aeroengines or full powerplants in which multistage compressors play a significant role. This overall process will be discussed in close alignment with an excellent publication on this subject by the director of engineering of Rolls-Royce /2/.

The *product definition lifecycle* is shown in Fig. 3.1. It consists of four sequential phases, starting from the initial investigations for a business case including technical concepts and throughout the in-service product support. These four phases are separated by clearly defined business decisions.

The sequential manner of the *product definition lifecycle* can not be changed to a parallel structure as gates with business and therefore budgetarial decisions have to be passed. This major process is continuously supported by activities ensuring the competitiveness of the company, e.g. technology acquisition, or by processes ensuring the internal requirements, e.g. staff hiring and budget availability.

3.1 Business Case Evaluation

The first phase of the *product definition lifecycle* is the proper evaluation of the business case, consisting of three elements:

- identification of the market need
- provision of technically feasible concepts
- development of a business case concept

The *identification of the market need* requires a continuous dialogue with potential customers. For multistage compressors their duty, application and environment have to be defined in detail. These will be summarised in the first issue of the specification containing items regarding:

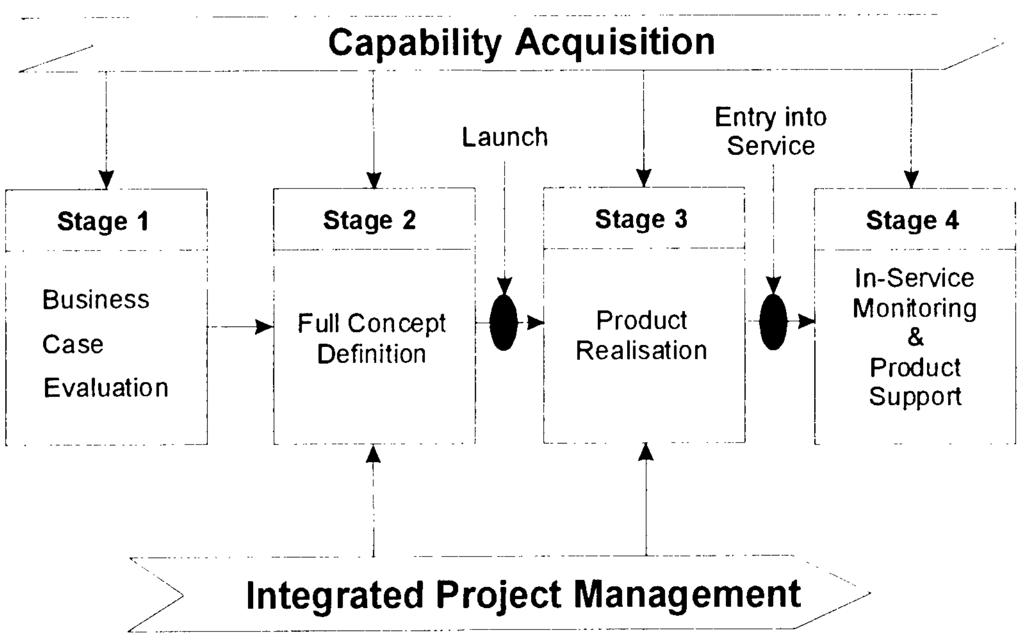

Fig. 3.1: The Product Definition Lifecycle

- performance, including off-design
- bleed requirements
- speed
- mean measures, interfaces
- reliability
- life
- maintainability
- noise
- weight
- cost
- time to market

Additionally certain important general design considerations, which have an impact on the freedom of choice of the designers, might be agreed, e.g. number of stages, blading technology standard, repeating stages, number of variable vanes, preferred material selections, direction of rotation, etc.

In the *concept definition* phase engineering will develop one or more compressor concepts. The task has to be achieved by a team of generalists, supported by representatives of all technical disciplines. Already in this phase interdisciplinary solutions are required to ensure the realisation of the product. A general risk assessment of the proposed solutions allows a grading. Critical areas, such as life limited discs, aerodynamic stability limits, critical joints, are investigated in greater detail. Based on the required technology and on the results of the risk analysis, demands for additional technology acquisition will be formulated.

The evaluation of the business case is complex and will not be discussed in detail in this lecture. An important influence is the general set-up of the intended contract with the customer. Engineering will provide the estimated cost of the product and the cost of the development.

The final establishment of the business case needs to take into account certain general boundary conditions of the company. These are the availability of the resources - namely budget, man power, test cells and test equipment - and the availability of the required technology. For the correction of deficits further investments or the selection of strategical partners are required.

At the end of the *business case evaluation* phase the business case has been established on the basis of a two-dimensional mechanical concept, in which design challenges were analysed in more detail and the identified remaining risks were judged.

The *business case evaluation* will conclude with a detailed concept review and - supposing successful pass - the *full concept definition* phase will be entered.

3.2 Full Concept Definition

The *full concept definition* phase is also known as the *preliminary design*. It is based on the information provided by the *business case evaluation* phase and comprises all the necessary work for a thorough project planning.

The definition of the full concept requires a significant build-up of the engineering resources. This will be the nucleus continuing through all following phases and requiring strong representation of all technical disciplines. For the refinement of the technical concept the interactions of the disciplines need to be analysed, introducing processes similar to those of the final product realisation. Basically the same computational tools will be used as in phase three, in risky areas even to the same detail. Less detail will be acceptable in areas which can easily be changed and which are uncritical.

The *full concept definition* phase is the last phase before launching a project and it can be assumed the future customer is known. Therefore the specification will be refined in a continuous dialogue to ensure that the right product for the customer's needs will be developed. For multistage compressors in jet engines the requirements for bleed parameters, namely massflow, pressure level and temperature will change and usually become more challenging. Based on more detailed information about the other turbomachinery components or for the improvement of the gasturbine cycle the working line will be optimised. Watching the available stability margin under critical conditions, this can have a tremendous effect on the performance of the engine and require detailed design changes.

Parallel to the refinement of the design, full activity plans have to be developed determining "what" has to be done, "how" and "by when". These plans need to be integrated in a full project plan, taking into account the master plan and its milestones. These complete plans enable the time and resource planning. In many cases this means shifting activities to different points in time or to different locations. The final suite of plans allows the identification of the critical path.

The project plan is the basis for the whole project and has to be reviewed and updated regularly.

The full concept solution is influenced by manufacturing, its capability and capacity, and the resulting cost. Potential manufacturers will be selected to start an early dialogue on manufacturing issues. This includes detailed discussions on the manufacturing methods, judgements of costs, cost reduction ideas, manufacturing envelopes, tolerances, lead times and availability of raw material. All these items may influence the functionality, life or reliability of the part. The responsible team leader has to ensure that the relevant specialists are involved and the best possible options are realised. Some of the decisions made at this early point in time will be difficult to be changed later on and might therefore create high additional costs.

Important decisions to be made for multistage compressors include the final definition of the number of stages, the annulus layout, the location and general design of bleed off-takes (inner and outer), the bearing arrangement, the material selections, the method of disk assembly, the design of the casings (split versus ring), the root fixings of the blades (axial or tangential), and the manufacturing methods of major or large parts. Detailed consideration of the maintainability of the compressor is required.

In analogy to the phase of *business case evaluation*, again the availability of capabilities has to be risk assessed and corrective actions have to be implemented to ensure a minimum risk in terms of capability availability.

During the engineering process *preliminary design* all design features are defined in the required detail. Besides performance, functionality, manufacturing, life and FMECA assessments, the selection of the material and the manufacturing method are focal points. No detail design drawings will be made. Tolerances will only be fixed if they have high influence on the technical solution and its costs. The objective of the *preliminary design* phase in engineering is to refine further the technical solution, to judge better the risks of individual concepts and to develop feasible solutions and feasible risk trees to all critical areas of the design. It includes the development of the validation plans.

At the end of the *preliminary design* a complex review will be held, the *preliminary design review*. It will review the main technical parameters as performance bids, life calculations and material selections. In addition the overall project planning will be revised by reviewing all plans and all requirements of resources and capabilities that will be needed, such as human skills, equipment, information technology, manufacturing capability and capacity, testing capacity, etc. Weak areas will be identified and suitable corrective actions will be developed and ensured.

The satisfactory pass of the *preliminary design review* represents the basis for the launch of the product.

3.3 Product Realisation

With the complete definition from the second phase, the "what", "how" and "when" has been defined and the process of the *product realisation* can begin. It consists of three major elements, namely design, analysis and development.

The objective of this phase is the full definition of the product, being ready for entry into service and meeting the contracted specification. The allocated short time scale to perform this task requires the change from individual sequential working practices to parallel and highly integrated processes. It highlights the need for a multidisciplinary approach, where all specialists are available simultaneously to define the final solution with all available knowledge as early as possible. The structure of this multidisciplinary team will be described in the next chapter. The high integration of disciplines in the overall design process of multistage compressors can be demonstrated best by typical examples. Here the blading process has been selected.

3.4 In-Service Monitoring and Product Support

The *in-service monitoring and product support* is the final phase of the propulsion system lifecycle. It is an interactive process between the manufacturer and the customer, ensuring continuous safety, reliability and performance of the product /3/. Currently advanced condition monitoring processes are developed to ensure both operational effectiveness of the product in service and up-to-date information for improvements in the design process /4/.

4. MULTIDISCIPLINARY APPROACH IN INTEGRATED TEAMS

Products of modern industry are inherently multidisciplinary. The degree of complexity and interaction of the disciplines generally increases with the technical standard of the product. Turbomachinery components, especially those in gasturbines, have reached very high quality levels. Further improvements of the components need to reflect the high degree of complexity in the team structure during all phases, the *concept* phase as well as the *product realisation* phase. While the primary task of a multistage compressor maintains to be the delivery of a certain massflow at a given pressure ratio and with high efficiency, this apparently simple task requires the creation of a complex system, in which several additional parameters have to be considered. Life requirements, durability and stability of flow are only few of these parameters. Fig. 4.1 gives an overview of the disciplines that have to be taken into account for a successful and quickest possible delivery of the compressor.

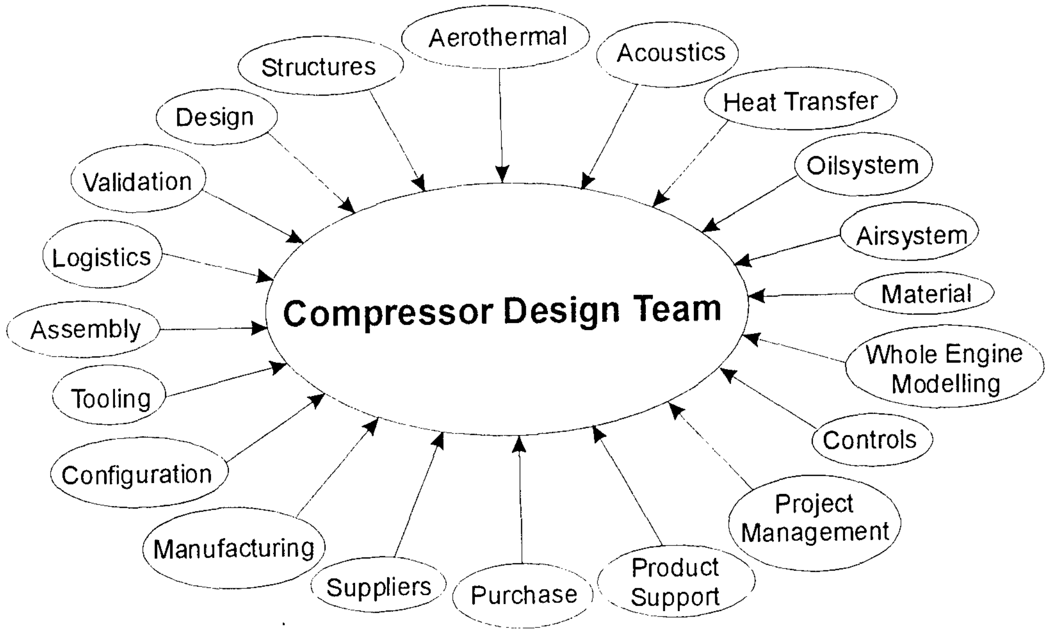

Fig. 4.1: Disciplines in Simultaneous Engineering Team

All compressor components are effected by aerodynamic requirements, aerodynamic and structural loads, heat transfer mechanisms and material properties. The structural loads need to satisfy the life targets. In addition to these primarily engineering oriented aspects further requirements need to be taken into account, such as manufacturing costs, weight, and maintainability. In the classical sequential approach, where the design process was split into different components and disciplines, each specialist was optimising in his assigned physical area of responsibility. Interactions between components or disciplines were uncovered during expensive product testing leading to a lot of corrective iterations. In addition these corrections may have adverse effects on other components, which due to the lack of awareness or communication might require several iterations until the project goal is reached. Besides high costs of late changes the time frame allowed for the development and thus the time to market, which is an important parameter for the fulfilment of the business case, might be in danger, resulting in a compromise between product performance and time to market.

The changes in the organisations which design modern products started from the recognition that an extremely high amount of knowledge and experience in all individual areas is already available at the beginning of the design phase, including a high amount of experience of the interactions between the individual disciplines. The major goal of the restructuring was to implement means to enforce the communication between the different specialists to ensure that already known interactions are taken into account in the first design already /5/. Despite the increasing availability of electronic communication tools, co-location of the whole staff being involved in the design process is beneficial. Based on these principles, simultaneous engineering was introduced. It can and should be applied during any of the previously described design phases /6/.

Fig. 4.2 shows the generic set-up of a simultaneous engineering team structure. It consists of representatives of all relevant disciplines and is structured according to the components, the general support functions and the whole engine issues. Aerodynamicists, designers and structural specialists as well as detailers will still provide the biggest portion of the compressor team. All other required experts with continuous interfaces, namely component validation, heat transfer, material, testing, configuration, logistics, assembly, product support, manufacturing and tooling, will either be permanently assigned to each single component or work in a separate sub-structure, the support functions. The allocation outside the component team very often results in a degradation of the level of communication. For multistage compressors which are part of complex systems, e.g. of jet engines, additionally to the component teams and the support functions there will be one or more "whole engine integration" teams, in which overall systems (air and oil), rotordynamics, performance, controls, overall validation strategies and others are dealt with. They will have an intensive and lively interaction with the component teams. As there is still the danger of insufficient communication, regular design reviews need to ensure that the interfaces are handled properly.

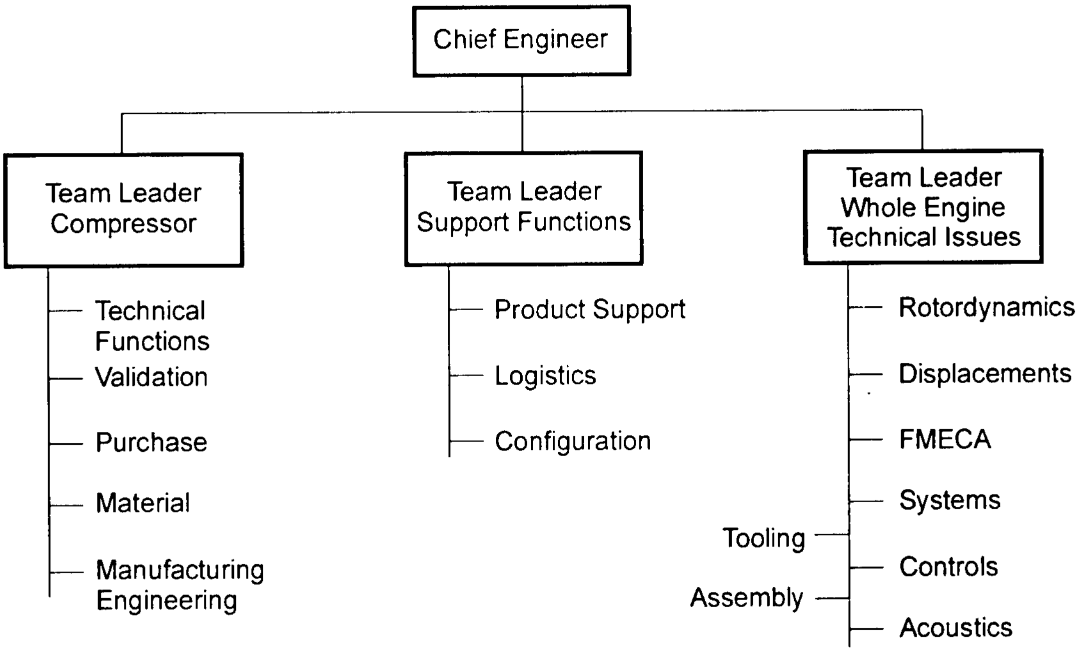

Fig. 4.2: Generic Team Structure

The team is headed by a team leader, who is responsible for the achievement of the specification of the product in time and in budget. Its structure only improves the human communication by setting identical objectives for engineers with different skills.

There are many possibilities for the structure of simultaneous engineering teams for multistage compressor design, their suitability depends on the individual frame provided by the project and the available staff. They all have in common the need for process orientation. Fig. 4.3 shows one classical possibility, where the compressor is split into different components and for each of these one specific task group is generated. For multistage compressors natural task groups are:

- blades and vanes,
- rotor-drum,
- casings,
- bearings and shaft,
- accessories,
- rig design.

Each component requires a specific representation of engineering technology. The task groups are headed by a task leader, who's responsibility for the component is analogous to that of the team leader for the whole compressor. In addition to the component groups, the team leader is supported by the additional general groups as described above.

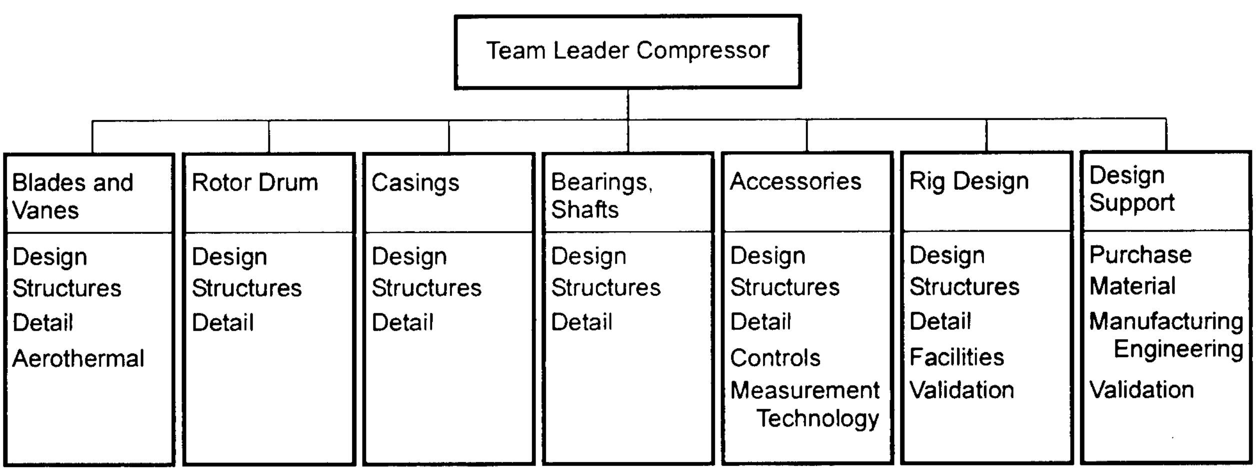

Fig. 4.3: Compressor Team Internal Structure

It has turned out to be beneficial to provide additional senior technical specialists' support on request from outside the component groups. This leaves more freedom to the senior specialist to decide on priorities and concentrate on the most critical items.

The group being responsible for blades and vanes includes the aerodynamic centre of the team. Its decisions finally determine the performance of the product. Beside aerodynamic considerations the internal process has to ensure that a high number of additional criteria is met. The next paragraph describes this interaction of multidisciplinary design.

5. BLADING DESIGN PROCESS

Substantial efforts have been made concerning the development of advanced blading, enabled by the continuous availability of cheaper and faster computers and by the availability of extended aerodynamic prediction methods. A significant know-how transfer has been started making technologies, which have been developed in the aeroengine business, available to stationary gas turbine compressor projects. Further improvements in the blading process in both achieved technical quality and reduction in development time require the integration of aerodynamics, design, stress and vibrational predictions into a single and powerful tool, which will then be used by the blading specialist, educated in all relevant disciplines /1/.

In today's business the time to market is an overall important parameter /2/. Advances in the speed of computational tools are therefore mainly used to reduce the duration of the design cycle. Especially in computational fluid dynamics (CFD), the design of the aerofoil shapes is passed to manufacturing, before all results of advanced tools have been produced and analysed. One of the time consuming routine operations in CFD is still the discretisation of geometry, which requires considerable improvements.

The purpose of this part of the lecture is to visualise the interaction of the disciplines and not to describe the most up-to-date details in technology required for blading. Excellent lecture series about the aerodynamic background have already been organised by AGARD and are available in the documentation. Some of them should be mentioned here: Lecture Series 167 "Blading Design for Axial Turbomachines", 1989 /7/, Lecture Series 195 "Turbomachinery Design Using CFD", 1994 /8/. A summary of the state-of-the-art aerodynamics in compressors is available in /9/.

Modern multistage compressors achieve performance levels that make the next improvement step even more challenging. This step then requires more effort and thus more budget. High investment is necessary for the development of advanced 3D blading, which is adapted to take secondary flow effects and blade row interaction into account. This trend has been enabled by the availability of more accurate 3D CFD-codes with reduced running time, making the computational multistage analysis an overnight job. This high technical standard shifts the emphasis from pure aerodynamic performance to the best multistage configuration, that works over a wide operating range with reliable high performance.

The heart of any multistage compressor is its thermodynamic performance. It reflects the quality of the transfer of mechanical energy into pressure increase and massflow of the fluid, facilitated by the pressure distributions on the rotating blade rows. Therefore, the careful aerodynamic design is one of the most important disciplines to be achieved in the design process. Today's tendency to thin blading with high loading and high Mach numbers increases the blades sensitivity for vibrations and for achieving reliable designs. The blading process has changed from a mainly aerodynamically dominated process to a highly interdisciplinary one. The general layout of the blading process is sketched in Fig. 5.1.

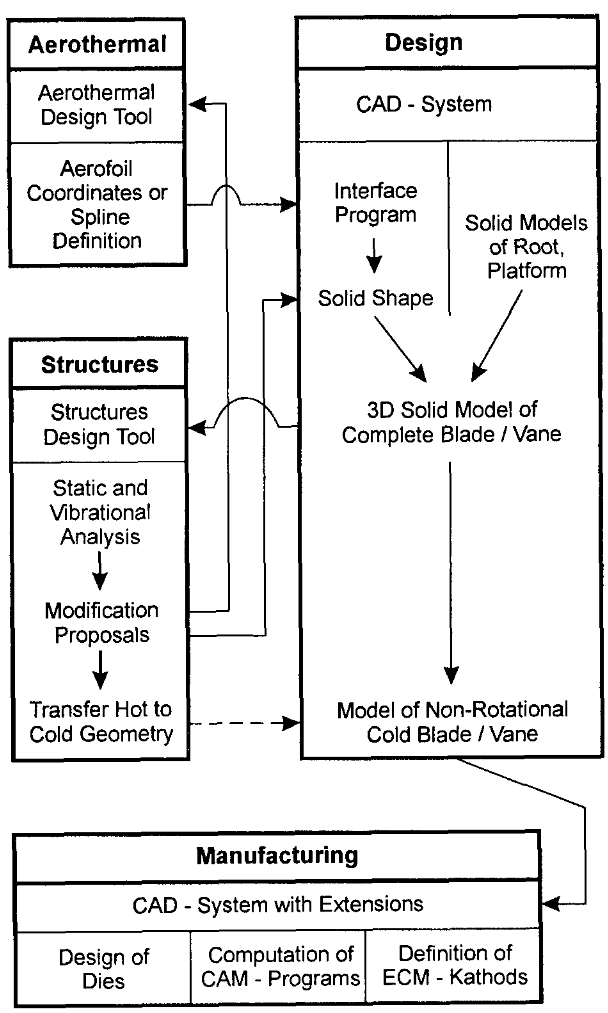

Fig. 5.1: Blading Design Process

The aerodynamic design of today's multistage compressors is usually based on the successful development of a product fulfilling similar requirements and improved by the results of sophisticated research activities. Starting from scratch introduces a significant risk of failure and of high related costs, as the individual aerodynamic parameters require very detailed matching, radially as well as between the stages.

The blading process starts with aerodynamic investigations. As soon as the first aerofoil-shapes are available, interactions with design and structures and vibrations start to produce a full model of the blade, including the root, and to determine the mechanical behaviour of this blade. The model is provided to manufacturing for cost and simplification assessment. This spreading of the information initiates intensive data exchange, which has to be based on consistent descriptions of the geometry, and initiates numerous iterations between all involved disciplines.

In earlier sequential processes the geometry description varied between the independently developed computational tools and inconsistencies, which, if detected, had to be corrected during a time consuming manual process. Further acceleration of the blading process necessitates improved tools, which are connected to one single database. In most companies projects are started implementing this unified data description. In many cases the requirements of data exchange between strategical partners were included.

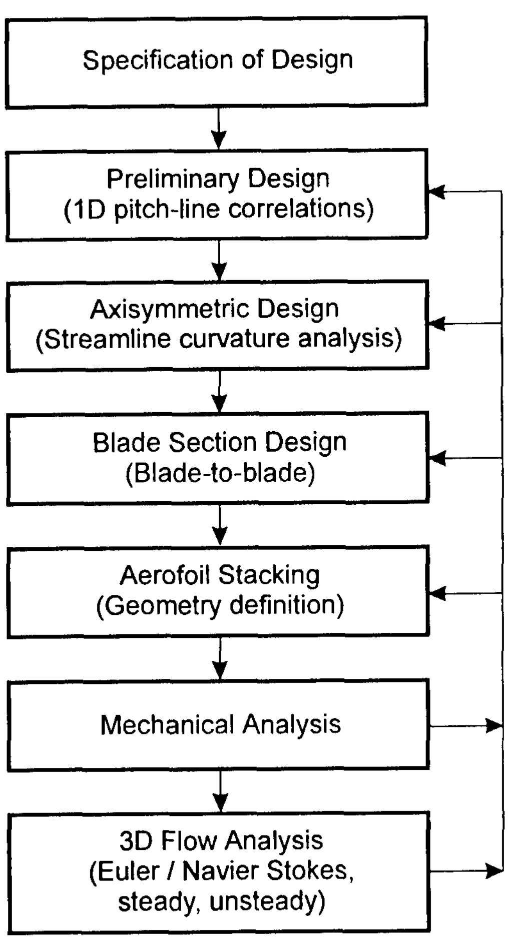

Fig. 5.2: Aerodynamic Design Process

5.1 Standard Aerodynamic Design Cycle

The definition of the annulus shape and the generation of the aerofoils is done sequentially by starting with an one-dimensional analysis and followed by stepwise refinements. Fig. 5.2 shows the progressive process, which includes iterations, if the expectations could not be fulfilled with the previously defined conditions. The next chapters discuss the basic steps of the aerodynamic design and highlight the multidisciplinary interactions to other disciplines.

Details of the individual methods are discussed in /10-14/

5.1.1 One-Dimensional Annulus Definition

At the beginning of the blading process the basic shape of the annulus has to be defined. This is one of the most important decisions within the project, as the complete compressor will be built around this annulus. At the beginning adjustments, which have only minor influence on the detail design solutions, will be acceptable. But the more the multistage compressor design is finalised, the less the possibility of changes will be allowed as these will affect a majority of parts.

The shape of the annulus will be designed based on the experience of the company and needs to be modified according to the planned work distribution in the compressor. Some companies prefer constant outer radii with increasing inner radii, see Fig. 5.3 top, others prefer constant inner radii in combination with decreasing outer radii, Fig. 5.3 bottom.

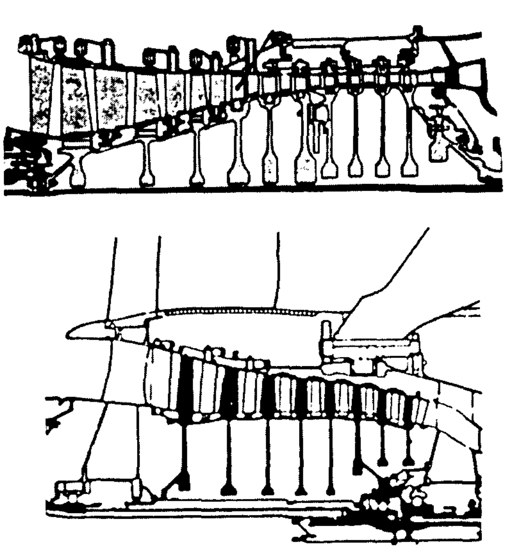

Fig. 5.3: Compressor Annulus

The design of the annulus and work distribution in simple means is done with an one dimensional model of the compressor. This is suitable for the concept phase only. The complete annulus is reduced to one streamline in the middle of the annulus cross section, reflecting the planned increase or decrease of its shape. At this point in time the intended stagewise matching is defined, one of the most important parameters deciding over the success of the development. The first analysis will only be made for the design point. The flow is discretised in the gaps between the blades. Based on the companies experience the input parameters will be defined in each discretisation position: area, pressure ratio, exit angle of the blades, speed, blockage and further parameters reflecting the blading. The program will derive the velocity triangles in front and behind each blade row. This one-dimensional tool is not able to predict the radial distributions of the parameters and is thus not able to take into account the radially increasing circumferential velocity. The computed velocities will allow the control of typical loading parameters such as De Haller and diffusion parameter. These numbers can again be compared to the companies experience and will allow first adjustments. The design specialists will be able to compare the stagger angle of the new blades and vanes with the circumferential space for each platform. Low manufacturing costs will only be achieved, if the platforms remain rectangular. As it is usual that during the development some blade rows need to be re-staggered, additional space for the rotation of the blade has be maintained, Fig. 5.4.

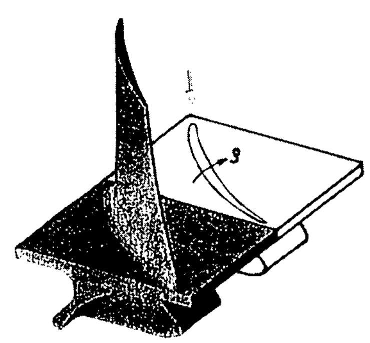

Fig. 5.4: Provision for Restaggering

5.1.2 Streamline Curvature Analysis

The next step of the aerodynamic design cycle is the determination of the radial distribution of the blading parameters. For this two-dimensional analysis streamline curvature programs are used. They start from the output data of the one-dimensional analysis and require further information about the intended radial distribution of the parameters. The mass flow of bleed extractions and the movement of variable vanes need to be simulated as well. The program will derive the position of the streamlines within the annulus which characterise the contraction of the flow as well as temperatures and pressures, velocity triangles and the loading parameters on all streamlines. The intended design can again be compared with previous solutions, but in more detail, as easy corrections can be fed into the process. All programs up to this point in time have worked with the flow angles to be achieved, the metal angles of the aerofoils are still unknown. Hence no design or structural investigations can be performed yet.

Streamline curvature programs allow the computation of off-design performance under certain limitations, but require additional parametric inputs. Current developments simulate radial mixing, which takes into account secondary flow effects /15/.

5.1.3 Blade to Blade Analysis

After the satisfactory completion of the hub to tip distributions of the aerodynamic parameters, the blading process continues with the blade to blade analysis. Its aim is to define the metal shape of the aerofoils under running conditions in several radial heights. The conservative approach is to define the blades in predefined streamline sections and to analyse their aerodynamic characteristics. By iterative modification of the shape an optimum solution will be generated based on the companies experience. The other process uses inverse design principles where the aerodynamic performance is prescribed and the computer program does develop the metal shape /16, 17/. It is common to use computer programs easy to handle with short turn around times for these first design iterations. Further improvements of the aerodynamic performance will be made after general mechanical aspects have been analysed.

After the definition of the blade in all cross sections the first full description of the metal is available. While aerodynamical tools for further detailed analyses are available and will be applied, it is similarly important to judge the structural and vibrational strength of the part. Therefore a complete data exchange takes place at this point in time and in parallel further aerodynamic investigations and structural analyses are performed, knowing that each will produce requirements for geometry changes.

5.2 Designing the Root and Platform

In parallel to the aerodynamic work described in paragraph 5.1, mechanical design works on the definition of the blade root and the platform. Two different root fixing principles are available, Fig. 5.5:

- circumferential root slots
- axial root slots.

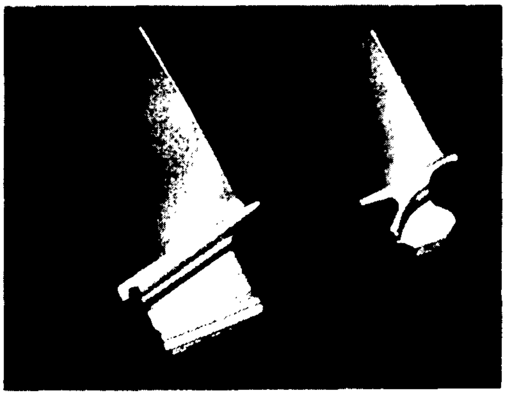

Fig. 5.5: Blade Roots

Circumferential slots are easy to manufacture. basically they require an additional turning process on the discs. Several solutions are available to ensure a minimum recirculation of the compressed fluid below the root: Sealing wings at the blade root. which seal under centrifugal forces. or separate sealing rings. The latter have the advantage of adding damping into the platform and providing additional freedom in designing vibration resistant blades. In circumferential slots the circumferential position of each blade is not properly determined. The blades will find their position under the increasing centrifugal forces. based on the aerodynamic load in an anti-rotational direction and based on the position of the neighbouring blade. A certain number of blades has special platforms with devices for locking nuts. fixing its circumferential position and closing the feeding slots in the circumferential groove. The number of locking nuts divides the circumference into a number of blocks of blades with equal distances. leaving a larger gap on the other side of the locked blade. This level of uneven distribution depends on the average cold gap between the platforms of the blades and the hot closure of the gaps. There exist designs. where under the hottest conditions the blades just touch each other. and other philosophies where the platforms are loaded circumferentially adding additional load onto the disk. The preference for the one or the other solution is as well dependent on the designing company's know-how. The effect of the uneven spacing of the blades and the remaining gap between the platforms at each locking nut on performance is difficult to derive and difficult to measure. While from an aerodynamic point of view it sounds beneficial to have even spacing. for vibrational behaviour the uneven distances might be used for positive effects.

The platforms of locking blades are weakened by the additional slot regarding structural and vibrational loads and require special attention. They are usually manufactured out of ordinary blades. with added operations to cut the slots into the platforms. A separate manufacturing route with e.g. thickened platforms adds significant costs.

Axial slots avoid the problem of uneven distributed blades. But the blades have to be fed from the front or the rear into the root. requiring significant radial depth and axial distances between the stages. providing the space for the neighbouring blades. These axial slots can be beneficial if combined with inner shrouds of the vanes. which are likely to be the best solution for variable vanes with a large radial extent. The manufacturing of axial slots requires an additional broaching operation on the disk with an additional risk of scratching surfaces. Axial roots can easily provide sealing to reduce the flow back from the downstream side of the blade row to the upstream side. For the exchange of one single blade only the required one has to be disassembled. Contact areas and resulting circumferential stresses between the platforms can be avoided completely. To improve the sealing. simple rubber strips can be glued below the platforms.

For the manufacturing of the blades itself axial or circumferential roots do not make big differences. Whether precision forged. electro-chemically machined or machined from bar or from forging. whether the root or the aerofoil are manufactured first. in all cases the rotation by 90 degrees only effects the fixture or encapsulation.

Non-variable vanes are usually held in circumferential slots. which are easy to manufacture in split casings and can easily be included in the split lines of ring casings. Fig. 5.6. While equal blade or vane roots and slots for different stages reduce manufacturing costs. they bear the danger of fixing the wrong blade to the stage. While the process can be well controlled in the initial assembly. the likelihood of maintenance errors should not be underestimated.

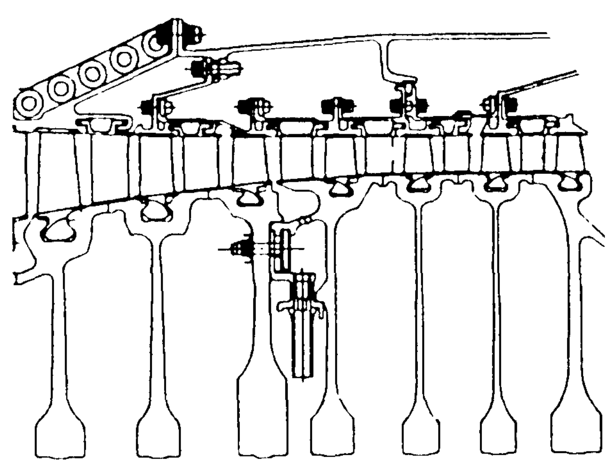

Fig. 5.6: Vane Root Design

5.3 Creation of Full Part

The aerofoil has been defined by the aerodynamicists and is available in their data format. It is transferred to the design (CAD) system. A consistent data structure and usage of identical polynoms at this point in time is important. Otherwise small differences in shape could not be avoided, eventually having significant influence on the performance. If different descriptions are used, the data should be re-transferred and aerodynamically investigated.

In the design system, root, platform and aerofoil will be brought together to become one single part. Special interdisciplinary decisions are required concerning the fillet radii and the location of the blade on the platform. At the latest at this point in time, manufacturing is involved, providing information about achievable quality, details about the leading edge and the number of bends in one surface and cost reduction proposals.

Stacking is the next element in the blade design process. For all rotating blades the bending moments due to the individual axial and circumferential position of the centre of gravity of each cross section need to be minimised. This is done by small translateral (non-rotational) movements of the cross sections such that the centres of gravity line up in radial direction. It is important for the designer to understand that this correction is only valid at one rotational speed, which is usually the design speed or the highest operating speed of the rotor, and needs to be agreed with structures and aerodynamics. The computational model at this point in time still reflects the hot running conditions, which are as well required for structures and vibration. Manufacturing requires the cold and unloaded equivalent, which can be recalculated using individual tools.

5.4 Structural and Vibrational Analysis

With this full definition of the part the structural analysis starts to derive steady and vibrational stresses and behaviour. As long as the aerofoil is not concerned, steady stress concentrations will be reduced by simple design changes which always effect the vibrational characteristics. Typical of modern blading in compressors are very thin aerofoils which are very sensitive to vibrations. Unfortunately the number of excitation frequencies increases with the number of stages, making the analysis of the vibrational behaviour an increasingly important element of the design. Fig. 5.7 shows an example of the Campbell diagram of a typical aerofoil, which due to the lines of the engine orders starting in one single corner is also called "spoke diagram". The abscissa parameter is the engine speed, the ordinate is the frequency. The straight lines starting in the lower left corner reflect the engine orders, the nearly horizontal lines represent

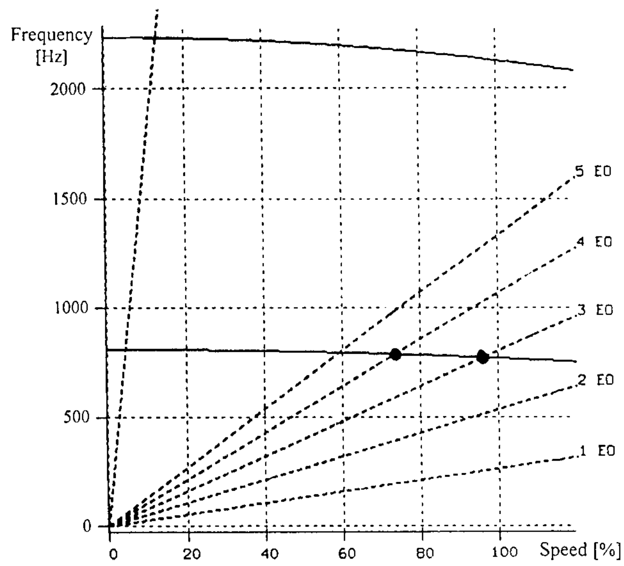

Fig. 5.7: Campbell Diagram

the eigenfrequencies of the part. These vary due to the stiffening effect of the centrifugal forces, which increase with speed. At each speed where eigenfrequencies and engine orders cross, the related vibration mode is in resonance.

The spoke diagram does not judge the intensity of the vibration level to be expected. To derive this the existing damping and excitation level in the system has to be known, where the latter in most cases can only be derived from measurements in the machine. It is common to use the so-called amplitude frequency (AF) diagram to compare the amplitude under a unity excitation with values derived from material properties or experimental vibration investigations. Each company will have individual guidelines about the acceptability of resonances. In general it can be said, that resonances close to the dominating operating point have to be avoided. Resonances in the running range should only be accepted if the strength of the resonance is known or if it can be guaranteed that the critical speed is always passed with quick accelerations or decelerations. In most cases resonances with the first eigenmodes are not acceptable. With the decreasing thickness of the blades and the modern bladings with end bends etc. the risk of failures in higher eigenmodes increases. The vibrational behaviour of the platforms requires careful consideration, with the inclusion of special blades as locking blades, oversize and undersize examples. In any case blade row interaction has to be analysed.

Theoretical considerations should always be backed up by experimental investigations. It is common to run an aerodynamic rig with a high amount of strain gauges on the blades and vanes for comparison with predictions /18/. Modern vibrational analysis tools do provide plots of mass sensitivity of the investigated part for each eigenfrequency. These diagrams provide a quick survey how resonances can be shifted with minimum change in mass distribution and how this change will influence the other vibrational characteristics. An intensive discussion between aerodynamics and structures and vibrations will define the changes to be introduced.

The previously described vibrational analysis can only be started after the part has been completed in design. The full design model requires valuable time which is lost for iterations between aerodynamics and structures. Therefore a short-cut solution is beneficial. see Fig 5.1., where the aerofoil alone which has just been designed or in addition with a platform and root similar to the expected one is analysed. The time saved balances the inaccuracy of this method.

5.5 Further Aerodynamic Analysis

Parallel to the mechanical process the aerodynamic characteristics will be analysed in more detail. High performance compressors require an intensive 3D analysis and today's computational methods even offer the possibility of the prediction of three-dimensional blade row interactions. These methods are not limited to the Euler Equations. the use of Navier Stokes Equations just requires additional computational power. But it needs to be pointed out that the high running times do not allow these computations to be used in numerous iteration processes.

The available technology allows the introduction of end bends correcting the effects of side wall boundary layers and secondary flow. This style of blading is not only challenging for the aerodynamicists. but for the persons that have to judge the vibrational behaviour. The detailed high tech analysis of compressor blading is described in literature in several presentations including AGARD /7,8,19,20/ and is continuous subject of the annual ASME Gas Turbine and Aeroengine Technical Congress.

All changes to the metal shape influence the vibration behaviour and require additional iterations.

5.6 Manufacturing Considerations

Manufacturing considerations play a significant role for the definition of the tolerances. Besides leading edge form and radius and surface roughness. a large number of detailed form parameters has to be optimised. Simultaneously quality control criteria have to be agreed. High reductions of manufacturing costs are possible in the design of the root fixings to minimise the number of necessary manufacturing operations (broaching instead of grinding or milling).

Blades and vanes can be manufactured in different ways. Most common to multistage compressors is precision forge. Fig. 5.8. A bar is cut to the right

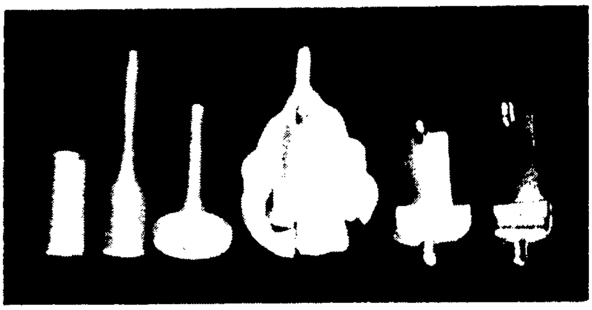

Fig. 5.8: Precision Forging of Blades

length and forged to the final aerofoil shape in few steps. The leading and the trailing edge are separately ground and will have a certain variation. For the root a block of metal extends from the aerofoil out of which the final root shape is manufactured. This operation requires the aerofoil to be encapsulated in metal with a low-melting point with high positional accuracy. so that it can be positioned in a special fixture. The root can be machined or just broached in few operations. The last operation is usually barrelling to a certain specification. which creates the final surface and the final radii

Precision forging is a cheap method for manufacturing high numbers of parts. but high initial investments are required for the forging tools.

For experimental use. low numbers and short manufacturing times machining from bar is the commonly used method. The machining time can be significantly high for hard materials. which are usually used in high pressure ratio multistage compressors. In general. there exist two methods. machining the aerofoil first or machining the root first. The achievable tolerances depend on the quality of the used fixtures.

In the meanwhile. electro-chemical manufacturing (ECM) is used more frequently. It produces at higher cost than precision forging. but provides better tolerance control. For parts with small tolerances. especially on leading edges. 360 degree ECM is required. This special method produces the shape of the leading edge during the chemical process and does not require additional barrelling for fine tuning.

Irrespective of the manufacturing method. the design data have to be transferred to the manufacturing data system. The same consistency rule applies as for the data transfer from aerodynamics to design. In manufacturing the data are used

- for the production of forging dies,
- for the programming of CAM machines,
- for the production of ECM dies.

In any case the provided data is to be modified to account for the specific manufacturing influences, e.g. for ECM for the local thickness of the chemical fluid.

5.7 Variable Vane Integration

The area ratio provided by the annulus of a multistage compressor is based on the compressibility of the fluid and the intended stagewise work distribution. At part speed the stages operate at lower pressure ratios, changing the overall matching of the compressor. The rear stages are unloaded, the front stages are higher loaded and their operating point shifts towards the surge stability limit. Two features are common to compensate the loading in the front stages:

- changing the vane stagger angle of the front stage with speed to correct loading,
- increasing the mass flow in the front by taking bleed.

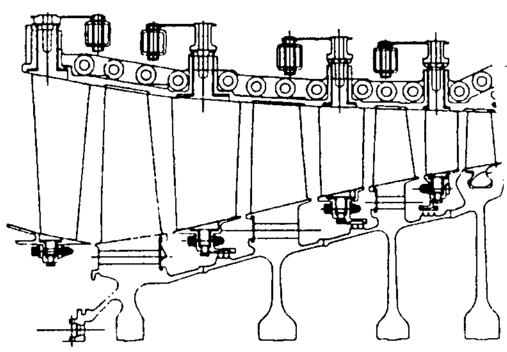

Fig. 5.9: Variable Vane Arrangement

The number of variable stator vanes (VSV) in the compressor is an early project decision, as any late correction is related to high additional cost. Fig. 5.9 shows a typical arrangement of variable vanes. The compressor has one inlet guide vane (IGV) and three variable stator vanes. The angular change is controlled by a mechanism on the outside of the compressor casing, Fig. 5.10. Therefore each vane aerofoil is lengthened by a short shaft, which extends from the annulus through the casing. The holes in the casing are exposed to the pressure difference between the inner pressure and the external pressure and lead to leakage out of the compressor. Minimum tolerances have to be introduced or special sealing and bearing bushes have to be used. These have to withstand all operational loads and contaminations like water and dirt. At the same time they have to ensure movements under all static and transient thermal conditions and long life under vibrations. On top of the shaft, special levers are mounted, which are connected to circumferential rings. These rings are positioned by a specific VSV actuation mechanism.

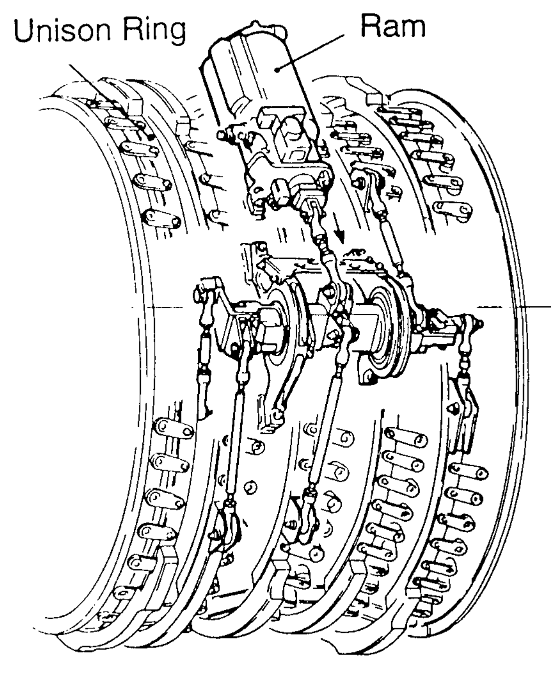

Fig. 5.10: Variable Vane Actuation System

The circumferential control of the stagger angle of all vanes is of great importance as the aerodynamic design does not assume any circumferential variance. This control can only be achieved by precisely controlling the tolerances of

- the vanes and spindles,
- the position of the holes in the casing,
- the concentric arrangement of the bushes,
- the angularity of the connection spindle to lever,
- the position of the holes in the circumferential rings,
- the concentric position of the rings on the casing,
- the capability of the actuation mechanism.

All of these tolerances require careful design consideration, and a sound balance between reduction in tolerance and cost reduction is to be created.

The tight positional tolerance of the holes on the circumferential rings is difficult to achieve under transient conditions, which change the temperature of the casing and of the ring with different time constants. Careful selection of materials for the rings and their centralising blocks is required. Nevertheless the remaining tolerances need to be measured and analysed in intensive tests. Fig. 5.11 shows the general diameter change of casing and ring during an acceleration. While at idle a certain gap between centralising blocks and casing exists, immediately after the start of an acceleration this gap closes, as the casing extends faster than the ring. The level of maximum interference is determined by the maximum force to be introduced or being available for the

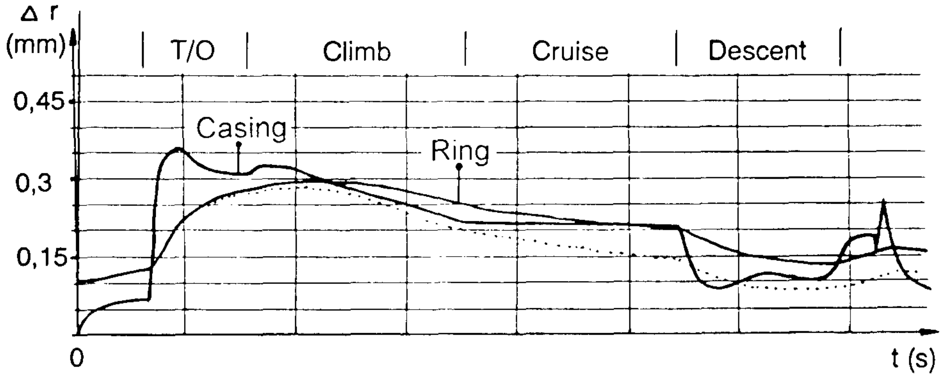

Fig. 5.11: Thermal Growth of Casing and VSV Unison Ring

rotation of the ring. With the heat up of the ring the gap opens up again at the end of the acceleration and reaches a maximum at stabilised conditions. The strength of interference and the change of the gap between hot and cold situation is a function of the selected material combination.

The design which allows the rotation of the vanes in the annulus requires an additional close co-operation of all disciplines. In the front stages, the annulus is characterised by a high rate of area contraction. Enabling the rotation of the vanes requires the introduction of specific gaps between aerofoil and the inner and outer annulus. These gaps change with the amount of required angular movement and lead to additional aerodynamic losses. During the development phase of multistage compressors it is not uncommon to choose even larger gaps to allow bigger movements for the optimisation of the design.

At the inner and at the outer annulus wall the aerofoil is placed on round platforms, the pennies. In annuli with contraction they can only be flush with the wall in one single position, which then is the minimum loss position. As soon as the vane is rotated, each penny creates steps in the flow, increasing with the angle of movement. Careful design is required to combine full functionality with low losses.

The variable vane schedule of a multistage compressor is the result of experimental optimisation. Variation parameters are:

- zero speed position of each vane
- degree of change with speed.

To reduce the risk of failing the experimental compressor, the optimisation starts at a low speed, e.g. 70% relative design speed. Each variable is varied around its initial position. The optimisation is repeated for increasing speeds until the fully opened position was investigated. To reduce the running time for the overall procedure, optimisation strategies have been developed. The overall optimisation requires a special actuation mechanism where either the vanes can be positioned independently and during the run, or where provision has been made to adjust the individual stages, the latter possibility being more time consuming. The effects on massflow, pressure ratio, efficiency and stability margin can be analysed. For compressors experiencing fast transients, it is common to optimise for maximum stability at low speed and maximum efficiency at high speed.

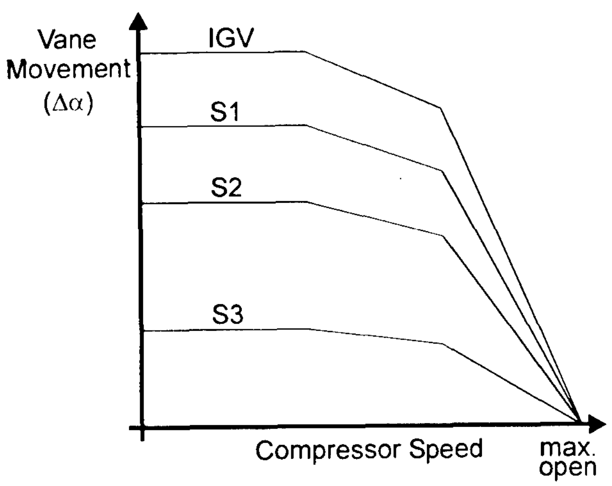

Fig. 5.12: Variable Vane Schedule

The resulting vane schedule will look similar to the one shown in Fig. 5.12, which is based on a four point optimisation with linear interpolation in between. It is important to recognise that the degree of angular change increases with speed. Small changes of speed close to the design point create big changes in angular position, possibly causing stability problems in the related control loop and as well introducing a significant amount of hysteresis. This hysteresis can be reduced by simply applying deltas onto the intended schedule, which depend on the rate of change of speed or by actually flattening the schedule with related loss in performance.

In general, positional accuracy and hysteresis is the challenge of the variable vane mechanism. The front stages require the highest amount of angular change. The most downstream variable vane likely moves only in the order of 10 degrees. If the mechanical tolerances and the mechanism control tolerances add up to just 1 degree, this is already 10% error at this stage. The hysteresis introduced by the control loop is in the same order as the mechanical hysteresis of the mechanism.

5.8 Bleed Slot Design

The stagewise matching of the compressor change with speed. One possibility of compensation is the above described vane variation. The second possibility for ensuring stable flow in the front stages at low speeds is the downstream extraction of bleed. This increases the massflow in the upstream annulus, thus reducing the blade row loading. The energy transformed into the bleed massflow is lost for the performance of the compressor. In jet engine compressors, bleeds are taken for:

- handling purpose,
- internal air system,
- customer (airframe) requirements.

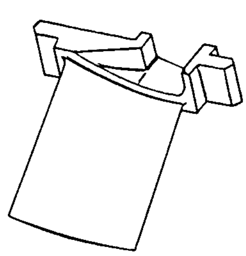

Fig. 5.13: Vane with Bleed Slot /18/

The last two are continuously required bleeds and need to be ducted out of the annulus with minimum losses. In the interdisciplinary design this is achieved by smooth slots in the stator platforms, Fig. 5.13 shows an early standard, or by continuous rings in the casing and rotor drum in combination with a proper aerodynamic design of the manifolds. Within those the Mach number and the losses are reduced by providing a larger area of a bleed slot integrated in a vane. This aerodynamically defined area needs to be integrated into the casing design. Simple solutions push the compressor outer casing to higher radii, which adds significant additional weight. A fair compromise has to be developed between aerodynamics, design, airsystem and weight specialists. Design solutions will impact the slopes of the casings, position and extend of flanges and heat shields, to name just the most important ones. All changes influencing the Mach number in the manifolds impact the heat transfer coefficient on the surface of the casing, thus modifying the thermal matching of compressor casing and compressor rotor drum.

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Recent Advances in Compressor Aerodynamic Design and Analysis

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ABSTRACT
Advances in Computational Fluid Dynamics (CFD) remain a significant source of improvements in the design process of aero-engine fans and compressors, leading to higher performance, cost and design cycle reductions as well as lower associated risks. This paper illustrates the continued integration of CFD tools at SNECMA with a description of the latest developments in compressor aerodynamic design and analysis methods. Three directions of research are currently being pursued.

Firstly, the numerical models are constantly improved to take into consideration problems as close as possible to the reality. This means in particular that turbulence models more representative of the real complex flows are introduced. Although it remains very incomplete so far, some unsteady effects are simulated. Also, the description of the compressor geometry is both refined, taking into account various technological effects (i.e. tip clearance; flowpath discontinuity; radius fillets), and extended to the simulation of multiple blade rows. The integration of new CFD tools with improved simulation capabilities requires a permanent update of the design methodology.

Secondly, a great effort is currently devoted to adapting the computing environment to the designer needs as it impacts both the quality and the overall duration of the design process. At SNECMA, this approach takes the form of a specifically tailored software environment in order to provide the designer « ready to use » tools, enabling him to fully exploit the potential of the methods and to focus primarily on the physical analysis of the results.

Finally, the most refined CFD tools present only a limited interest to the compressor designer unless they have been extensively validated on significant experimental test cases. This implies that an appropriate validation database representative of real engine flows be acquired.

All these aspects of CFD are illustrated in the paper using practical examples supported by both numerical and experimental results. Finally, the prospects of new developments are discussed.

1. INTRODUCTION

The design of advanced aero-engine fans and compressors has to meet ever more demanding requirements. Higher performance must be achieved within shorter design cycles and at lower cost. Ambitious objectives in the reduction of weight, complexity and manufacturing costs lead to fewer compressor stages, and therefore to increased stage loadings.

For compressor designers, this new situation implies the capability to control the very complex flow phenomena occurring in highly loaded stages, on the whole operating range of the compressor, early in the program. In addition to aerodynamic performance, the aggressive design of advanced, fully 3D blades also requires an early focus on all the aspects related to engine mechanical integrity : blade flutter and forced response as examples.

Up to the end of the 70's, most of the design and optimization process relied on an empirical approach, which meant a very large number of tests. The all-experimental optimization strategy was very time and cost consuming for two reasons at least. Each iteration implied all the phases from design to manufacturing, instrumentation and testing. Secondly, determining what had to be improved in the design required a comprehensive instrumentation on real engine components, which was strongly limited by technological constraints. As a result, it was very difficult to identify the potential problems and even more difficult to understand them.

For these reasons, SNECMA started very early to take advantage of the fast-growing computer power and of the concurrent advances in Computational Fluid Dynamics. This approach has been greatly rewarded as the introduction of CFD tools in the design methodology has brought major improvements in the iterative optimization process of fans and compressors. For example, the impressive results obtained on fan design (Figure 1) within a relatively short time, have demonstrated that the use of CFD is a successful tool to achieve continuous improvements in aerodynamic performance, and also to shorten design time scales and reduce cost.

An attempt to summarize this contribution could use the following keywords : faster response, broader range of alternative solutions, better description of flow complexity. Indeed, every computation node in a numerical simulation is also a « measurement » node, which allows an easy and comprehensive analysis of the flow prediction.

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Unfortunately, CFD is still far from faithfully reproducing reality. Even with the power of the most recent super computers, simulation capabilities still depend on very approximate physical models or are limited to component parts. The computation of a full multistage high pressure compressor with 3D, unsteady and viscous, small scale phenomena is out of reach for a long time yet. As a result, the major challenge for both the engine component designer and the CFD method developer consists in integrating new computational methods, with their capabilities and limitations, in the design process in a fast, safe and efficient way. Every new method brings new answers, but also raises new questions. The most obvious risks in using a new, more powerful tool are either misunderstanding or overoptimistic confidence in the results.

A constant effort must therefore be dedicated to the comparison, validation and calibration of methods. This means in particular that heavily instrumented rigs, representative of real engine flows be used to produce an appropriate validation data-base.

At SNECMA, a strong interaction between compressor designers and CFD tool developers has always allowed an early use of advanced methods in the design process : 3D Euler in 1984, Quasi-3D Navier-Stokes in 1988, 3D Navier-Stokes in 1992. The recent development of parallel vector computing and workstation network now makes possible the use of multistage 3D Navier-Stokes in the design process of multistage compressors. Most of those recent CFD developments have been undertaken in close co-operation with research laboratories such as ONERA, LEMFI (University of Paris VI) and Ecole Centrale de Lyon.

This paper presents the aerodynamic design and analysis process of fans and compressors at SNECMA. Following a general presentation of the design methodology, the compressor flowpath and blade design tools are exposed. Then, analysis tools are described with a particular emphasis on the numerical basis of currently used CFD codes and on the combined efforts to develop homogeneous and user friendly pre and post-processors. The performance prediction capabilities of analysis methods are illustrated by a comparison with experimental results obtained from an advanced transonic compressor stage and a basic tip clearance experiment. The paper continues with a description of aeroelastic and aerodynamic compressor instabilities along with the associated methods used to simulate them. Finally, conclusions are drawn on the current use of CFD tools in the compressor design process and new directions for improvement are proposed.

2. EVOLUTION OF COMPRESSOR AERODYNAMIC DESIGN PROCESS

The efficient integration of new computational tools with increased simulation capabilities is a real challenge for the designer. To take advantage of the fast advances in CFD developments, the design methodology and procedure must be constantly adapted according to new simulation capabilities. Improvements have therefore been brought to the methodology presented by [Falchetti, 90], [Brochet, 93] and [Vuillez, 94]. All these papers already pointed out the importance of CFD methods and the improvements they can bring to the design of fans and compressors. As an example, the fan of the CFM56-5C which powers the Airbus A340 was designed using 3D Euler and Quasi-3D Navier-Stokes solvers whereas the CFM56-7 large chord fan design for the latest Boeing 737 family is based on 3D Navier-Stokes calculations.

The demonstrated outstanding performance achieved by this recent design shows that the use of CFD is not only an excellent tool to improve efficiency but also to shorten time scales and reduce costs.

The current methodology is still basically an iterative process since some steps often need to be repeated before achieving an acceptable solution. Figures 2a & 2b summarizes the procedure used to design HP compressors.

At the very beginning of the process, a 1D calculation called the pitchline is usually performed in order to choose the number of stages and a preliminary general shape of the compressor (rising or falling line). A preliminary stage loading distribution consistent with the overall specifications is prescribed throughout the compressor. This 1D approach also gives the opportunity to assess very quickly some other important parameters such as the rotor weight. At this very early stage of the design, a preliminary optimization is conducted. This first step mainly concerns high pressure compressors.

The next phase of the design process is based on an inverse axisymmetric throughflow computation which yields the velocity diagrams at a specific design point. A direct throughflow calculation is then carried out in order to assess the off-design behavior of this compressor. This approach allows the designer to choose some other operating points as objectives for blade design : three operating points are usually considered as necessary to correctly adapt the blade shape to the different incidence objectives. For HP compressors, several aerodynamic design constraints are typically accounted for at nominal speed on the operating line and at nominal and part speeds near stall. The inlet boundary conditions for the blade analysis phase are taken from the previously mentioned throughflow data at design and off-design conditions.

A major new step has recently been introduced in the blade analysis phase by accounting for technological effects such as radius fillets, rotor tip clearances or buttons of variable-stagger stator vanes. The current full 3D Navier-Stokes code is now capable of predicting the main consequences of these effects which are considered to be significant in the matching of high pressure compressor stages. From a practical point of view, the level of consistency achieved between 3D calculations and throughflow objectives is driven by the industrial know-how based on past experience. The discrepancy observed between 3D and throughflow models highlights the limitations of the classical approach which splits the real flow in two two-dimensional flows called S1 (blade to blade) and S2 (hub to casing). The steady multi-stage 3D Navier-Stokes code introduces a major change in the design process since it is no longer necessary to prescribe aerodynamic conditions from the throughflow model at the interface between blade rows. This new multi-stage tool is now fully integrated into the design methodology even though the analysis of a new design is always initiated using single blade row calculations. As a matter of fact, it appears to be more efficient to initiate the design with rapid calculations and ultimately to check the whole compressor operation with more elaborate tools such as the multi-stage code.

The use of advanced tools allows the designer to enhance the inlet specific flow of fans and to increase the mean stage loading of HP compressors while ensuring adequate stability margins.

2.1 Through flow calculations

As for all engine manufacturers, the throughflow method is the basis of compressor design at SNECMA. It allows a complete definition of the flowpath geometry as well as velocity diagrams for each blade row. For all further steps, the meridional flowpath represents a reference which gives a simplified but comprehensive overview of the whole compressor geometry and operation.

The code uses a classic streamline curvature method. The input parameters for the inverse mode are spanwise distributions of rotor pressure ratios and stator exit angles. The calculation output is the velocity diagrams at several locations, generally the leading and trailing edges of the blades. But the final result strongly depends on the losses and blockage due to the boundary layers developing on the endwalls from the inlet to the compressor outlet. The axial velocity and thus the stage matching are closely associated with these parameters.

The classical 2D viscous and shock losses are well predicted by using semi-empirical correlations based on past experience but a large proportion of the global losses is produced near the end-walls as a result of secondary flows (blade tip clearances, shroud seal leakage, hub corner vortex...). These flow phenomena strongly affect the mass flow distribution along the span which has to be predicted in the throughflow phase. Basically, it can be seen as a deficit of axial velocity near the endwalls whereas the velocity is higher at mid-span. As a result, large modifications of incidences and deviations may occur, and are of first importance for the stall margin and efficiency control. The prediction of endwall effects is a major difficulty in multistage compressor design. Since 1984, SNECMA uses a method originally based on the MELLOR theory [Mellor, 1971] with continuous refinements to incorporate the results of compressor tests. In complement to this throughflow approach, the systematic use of single and multi-stage 3D Navier-Stokes analysis enhances the capability to deal with endwall effects in the multi-stage environment.

Another important point of throughflow analysis is linked to the large variations of pressure and temperature along the span caused by endwall losses. A model of radial diffusion effects has also been implemented in the current SNECMA throughflow code. The importance of radial mixing in multistage compressors has been emphasized for example by [Gallimore, 86]. SNECMA's model has been calibrated by application to several tested multistage HP compressors that cover a wide range of applications (civil & military, 6 to 10 stages). To illustrate this effect, [Vuillez, 94] shows a good agreement between experimental data and the throughflow model on a high speed research vehicle. This test vehicle is representative of the rear stages of a civil aero-engine HP compressor.

2.2 Blade design

Each blade design starts with the design of several profiles along the span. Different methods are used depending on the inlet mach number. All these methods integrate mechanical constraints such as maximum of thickness to chord ratio, leading edge and trailing edge thickness.

Subsonic and mildly transonic profiles are designed using a Quasi-3D inverse method. It has been developed jointly by ONERA and SNECMA and is described in [Nicoud, 91]. This method solves the Quasi-3D compressible transonic potential equations by a finite element approach. The Quasi-3D model takes into account the radius and stream tube variations as well as rotational effects given by the throughflow computation. Using a transpiration model, the inverse formulation iteratively modifies a preliminary profile to match the imposed velocity distribution on the target profile. This procedure allows a good control of boundary layer diffusion.

The aerodynamic performance of the profile is then analyzed using the Quasi-3D Navier-Stokes solver described in [Vuillez, 90]. The profile can be further modified according to the prediction of viscous effects and shock losses.

Supersonic profiles are designed using an aero-geometrical method developed at SNECMA. Some input parameters are specified, such as suction side incidence, pitch-to-chord ratio, turning angle, deviation, throat margin. Iterations with a Quasi-3D Navier-Stokes direct solver are necessary to reach aerodynamic design objectives and minimize shock intensities and boundary layer diffusion.

In order to have a single and more accurate inverse design method, a Quasi-3D Euler method has recently been introduced in the design process. It was originally developed by the Von Karman Institute and is described in [Leonard & Van den Braembussche, 1992; Demeulenaere, 1993]. This method solves the Quasi-3D Euler equations by a finite volume approach. Like the inverse potential method described previously, an optimized profile is obtained after 3 steps. A target pressure distribution is first prescribed on an initial profile (step 1), then the quasi 3D Euler equations are solved using a finite volume approach (step 2) and finally, the new airfoil geometry is derived from a transpiration method. This Euler method is appropriate to both subsonic and supersonic flows, and enables shock intensity to be controlled. The results obtained are in good agreement with a quasi 3D viscous analysis.

Figure 3 illustrates the interest of using a Euler approach over the potential inverse method. The case of a high pressure stator vane airfoil with an inlet Mach number of 0.9 and high flow turning is presented. The isentropic Mach number distributions computed by a quasi-3D Navier-Stokes code are shown for two blade profiles. The first blade profile is that typically obtained from the potential inverse method. The second blade profile geometry has been optimized using the Euler inverse method. The high flow acceleration on the suction surface of the airfoil has been substantially reduced using the Euler method and consequently shock losses have been minimized.

As described in the following sections of the paper, SNECMA analysis methods solve the 3D viscous flows and a great effort has recently been devoted to speeding up these computations : about two hours for a single blade 3D Navier-Stokes computation nowadays instead of more than 20 hours in 1991. As a result, these solvers can now be used as a basis for 3D Navier-Stokes design methods. This will be the next major step in the evolution of design methods.

3. DESCRIPTION OF ANALYSIS TOOLS

The use of advanced numerical methods is an efficient and powerful way to analyze and design high performance turbomachinery bladings. For several years, SNECMA has devoted considerable efforts to the introduction of new analysis codes into its engine component development methodology [Karadimas, 1997]. The aim of all efforts dedicated to CFD developments is to increase the capability to accurately simulate the very complex flows encountered in turbomachinery, i.e. three-dimensional, compressible, transonic and supersonic, viscous, unsteady and turbulent flows.

The first issue arising about CFD tools is the level of modeling required and the associated cost (in terms of time and computing facility required) of such simulation. For industry, the answer comes from close co-operation with different research partners, and requires a permanent foresight of computer technology breakthroughs and availability, as well as new developments in numerical techniques. In many cases, SNECMA played a leading role in fostering new research work. Cost evaluation is a key point. The fast cost decrease for a given computing power requires to carefully choose the right time for acquiring new computing capabilities : too early is expensive and can be hazardous (one has to remember the promise of Massively Parallel computing in the early 90's), too late means using tools that are poorly competitive.

Then, having a new tool -cost efficient to use-, we need to validate and calibrate it. A compressor designer can take no advantage of advances in CFD techniques without adequate experimental data to validate and calibrate new generation codes. This means that combined efforts are clearly needed in designing, manufacturing, instrumenting and testing experimental rigs capable of bringing ever more detailed and reliable information on flows in engine-like components. In fact, it must be emphasized that the use of CFD in aero-engine design strongly depends upon the improvements in measurement techniques, in order to have access to the same detailed level of investigation as that of CFD (e.g. secondary and unsteady flows). Data acquisition on real engine components is important as well, but it cannot be considered sufficient, since the constraints specific to engine design make it difficult to implement enough instrumentation to directly validate advanced CFD tools.

Last but not the least, the methodology has to be modified to successfully and efficiently integrate the new tool. Up to this decisive step, only code developers familiar with computational techniques have been involved. The final objective here is to move from a solver to a tool that can be handled by designers who are not CFD specialists. To reach this objective, additional work is required to integrate the new code in a framework that is user-friendly. Moreover, simple user rules must help the designer to feel comfortable with advanced tools, which bring new answers but also question more traditional design procedure. The computing environment must ease intensive use of the application, so as to enable positive user feedback. We can think of the interaction between code developers and end-users as an integrating circuit loop (Figure 4 « Integrating CFD in compressor design ») whereby the experiences of both teams get integrated into a methodology, whose output is amplified by the available processing power, resulting into advances in compressor design.

Within SNECMA, this problem is tackled through the association of research and component designers within the same entity. CFD developers are thus spread in different departments such as Compressor Aerodynamics. This allows component designers to be involved early in the validation and industrialization of new codes. Once the code is in service, CFD developers can assist users in real time. A strong co-ordination guarantees the necessary synergy between the developments undertaken within each department.

From a general viewpoint, a new application is considered operational once the complete cycle of pre-processing, computation, post-processing and interpretation of results can be executed twice a day. This means in particular that the calculation itself can be run overnight, analysis and re-design in the morning so as to obtain another analysis -and re-design- at the end of the work day. This objective can only be achieved by integrating from the early beginning computer performance and ergonomy objectives into the application. As new CFD tools are increasingly CPU and data processing intensive, all the aspects of CPU optimization, computer scheduling and management, data transfers and storage have to be analyzed. For instance, single blade 3D Navier-Stokes computations have been implemented in the design process in 1992 with these constraints in mind. Nowadays, in the course of a design cycle, more than 10 computations are performed every day within the compressor aerodynamic department.

3.1 Navier-stokes solvers

In the 70's and the early 80's, different codes were developed separately for different applications. The poor memory capabilities of the computers put severe restrictions on code structure. CPU time considerations required a deep optimization of the software coding on a single direction. As a result, each code would live its own life, would be dedicated to a given application and would include its own pre and post-processors.

The outstanding development of computer technology in the 80's and the advances in numerical techniques made possible a large number of new applications for CFD. For the industrial user, this led to the obvious necessity to structure the new developments from a global point of view. There are two main objectives. Firstly, all applications, either steady or unsteady, 2D or 3D, inviscid or viscous, must benefit from the work on any of them, in order to save time and money. Secondly, the amount of work necessary to maintain the codes and support users must be kept at a reasonable level. Hence, applying solutions at a larger scale makes it possible to optimize development resources. For instance, pooling Graphic User Interface (GUI), pre/post-processing and data management between different applications results into fewer redundant programming and testing operations.

Nowadays, most of SNECMA solvers for compressible flows share the same modular coding and the same numerical basis, which will be described hereafter. This makes it faster and easier to validate and compare codes for a broad range of applications, i.e. compressors, turbines, air intakes and nozzles.

The latest numerical developments at SNECMA come from two long time co-operations with :

- ONERA for the « CANARI » code
- LEMFI for the « TURBO3D » code specifically designed for unsteady computations

Originally developed by ONERA in the early 90's CANARI is the standard 3D Navier-Stokes solver commonly used at SNECMA in the design process. The numerical scheme used to solve the compressible flow equations is a finite volume, time-marching technique applied on multi-domain structured grids. Structured grids are well adapted to blade-to-blade geometries which present a simple topology. The multi-domain approach offers a good compromise in order to benefit from structured grid simplicity and yet guarantee satisfactory qualities in terms of mesh regularity and orthogonality. The numerical scheme includes two steps : an explicit integration scheme and an implicit residual smoothing step. The explicit step is a centered cell-vertex space discretisation combined with a four-step Runge-Kutta time integration scheme. An additional numerical dissipation has been derived from the second and fourth order Jameson and Turkel to ensure the stability of this explicit step. Also, an implicit residual smoothing technique proposed by Lerat [Lerat et al, 82; Lerat, 85] is used. For steady computations, local time-stepping achieves faster convergence rates, thereby maximizing computing efficiency.

All boundary conditions are imposed through compatibility equations obtained from characteristic relations, as well as sub-domain matching. Finally, the turbulent closure of the Reynolds-averaged Navier-Stokes equations is obtained from the algebraic mixing length turbulence model of Michel [Michel, 69]. The use of an algebraic turbulence model guarantees good code robustness, with a reasonable accuracy, even if the extension of such a model to 3D applications [Vuillot, 93] requires special care to account for the influence of multiple solid boundaries.

This numerical core is identical to other CFD tools such as 3D-Euler and quasi-3D Navier-Stokes. As shown later, the multidomain approach has been widely used for multi-blade simulations.

Yet, to be able to predict the flow fields in the case of high « aerodynamic constraints » (such as important 3D effects, high pressure gradients,...) or unsteady effects, the development of higher accuracy turbulence solvers is needed. Developed by the Fluid Mechanics research laboratory (LEMFI) of CNRS for Rotor/Stator simulations (« Forced response project »), the TURBO3D code solves the compressible Favre-averaged Navier-Stokes equations, with a closure of the turbulence terms proposed by Launder & Spalding for incompressible flow with two transport equations for k, the turbulent kinetic energy and ε, its dissipation rate. This « high-Reynolds » model is appropriate to the freestream (away from wall). In order to deal with boundary layers, the constant of the model can be modified to take into account the eddy viscosity near the wall. This leads to a « low Reynolds » model. The Launder-Sharma near-wall k-ε turbulence closure is used in the code to deal with the semi-empirical transport of the modified dissipation rate ε^* [Launder & Sharma, 1974].

The numerical method of the code is described in detail by Vallet [Vallet, 1995; Gerolymos & Vallet, 1996]. The mean-flow and turbulence transport equations are expressed into the cartesian coordinate rotating frame and are discretized in space, on a structured grid, using a 3rd order upwind-biased MUSCL scheme and Van Leer flux vector splitting with Van Albada limiters. The resulting semi-discrete scheme is integrated in time using a 1st order implicit procedure. The resulting scheme is highly robust and efficient.

With the latest code developments (CANARI & TURBO3D) and the new computer languages (« Object Oriented Languages, Internet Technology,...), the scheduling of a new « Multi Purpose & Multi Environment » CFD platform becomes a reality. The ONERA CFD project named « elsA » (for « Ensemble Logiciel de Simulation en Aérodynamique ») will meet the industrial needs : a new modular, flexible and scalable structure. ElsA will enable us to integrate different solvers from different research teams in order to obtain the most cost-efficient simulation for a complex problem. With this kind of tool, the simulation of a new complex problem will look like a modular and extensible construction assembly game : the assembly of different modules (the most appropriate modules for a given problem) to perform the complete simulation.

3.2 Pre and post processing tools

A high quality modular solver is not sufficient to obtain industrial-grade CFD tools. Fast and precise simulation tools are not much helpful if the time and man-power required to build the simulation test case and to analyze it is too important.

Due to the simplicity and repeatability of the compressor geometry, the benefits of structured multiblock meshes can be fully exploited : simple algorithms, easy coding,... As a result, SNECMA has been able to develop its own dedicated mesh generator and associated pre-processing. This mesh generator is based on few « external parameters » (less than one hundred) which can be « graphically » modified to obtain an « optimal » (in terms of quality) mesh. Then, the « batch » version generates one million mesh points for a single blade 3D Navier-Stokes grid in less than one minute on standard Silicon Graphics workstations.

To account for technological effects -such as radius fillets- additional processing is performed on the standard mesh. To guarantee future demands and evolution those tools have been developed using « Object-Oriented Languages ». Additional functionality -as by-pass flow separator, mid-span shroud- are implemented by merging different standard meshes.

Finally, the aim of pre-processing is to collect data and requirements from the mesh generator, throughflow computations, and user demands, to define the input grid and boundary conditions of the solver and the aerodynamic input. Initialization is directly provided by throughflow data for steady computations, then altered as needed to account for boundary layers developing at endwalls. Additional inputs are taken into account for unsteady calculations, like blade vibration modes for flutter simulation for instance.

To be efficient, post-processing tools must offer several levels of investigation. A straightforward, batch tool is necessary to obtain reduced data, providing fast answers even from heavy 3D Navier-Stokes computations. This is particularly convenient in parametric studies around a configuration close to the final one. It provides spanwise distribution of standard flow quantities, or pressure distribution on blade profiles. But a deeper and interactive investigation may be necessary, with strong 3D visualization capabilities. At SNECMA, the solution consists in the combination of in-house, modular tools specific to turbomachinery applications and of 3D visualization software from vendors.

3.3 Simulation environment

Last but not the least is the simulation environment, which is an aspect of CFD not related to numerics, physics nor turbomachinery. At first sight, it may seem to go beyond the activities of the compressor aerodynamics department, but its functions are essential as they have a strong impact on the overall quality and swiftness of the design process. Code environment can be split into two parts : user environment and computer optimization.

The user environment has to be as simple as possible and most important it should be independent of the computer platform. To meet these requirements, SNECMA has developed a custom Graphic User Interface using GNU utilities and World Wide Web tools : HTML & Java languages, Internet browser, HTTP/CGI server. As a result, the compressor designer can use CFD tools which have been specifically tailored to their needs while using low cost, high quality and no vendor specific software developments.

To obtain high performance CFD tools, it is essential to have efficient algorithms but also an overall simulation approach which is computationally efficient (in terms of elapsed computer time). In the early 90's, SNECMA had highly vectorised and parallel solvers on a Cray YMP. Nowadays, both directions of optimization (vector & parallel) are still pursued on a Fujitsu VPP-300 computer : very high vector performance on each processor and a parallel approach for multi-bladerow simulations. This is performed using the in-code multidomain property of a multi-bladerow simulation (e.g. rotor/stator or multistage simulations) and a parallel tool like PVM or Calcium (a code coupler from EDF-Electricité de France). This strategy has also been applied on a workstation network for code testing and small mesh computations.

4. APPLICATION OF ANALYSIS TOOLS TO THE PREDICTION OF COMPRESSOR PERFORMANCE

For the compressor designer, the most refined CFD tool presents only a limited interest unless it has been extensively validated on representative experimental test cases. As mentioned in the introduction, the most obvious risks in using a new, more powerful tool are either misunderstanding or overoptimistic confidence in the results.

A constant effort must therefore be dedicated to the comparison, validation and calibration of methods. This implies that an appropriate validation database representative of real engine flows is available. At SNECMA, this important need is satisfied by designing and conducting experiments at three different levels covering a wide range of measurement resolution and relevance to engine geometry :

- **basic flow experiments** (ex. NTUA tip leakage annular cascade) - simple geometric and flow configurations - highest measurement resolution
- **laboratory compressors** (ex. CME2 subsonic stage) - fairly representative of geometric and flow configurations - good measurement resolution
- **research compressors** (ex. ECL4 advanced transonic stage) - fully representative of engine geometry and flow conditions - lowest measurement resolution

4.1 Description of experimental test cases

4.1.1 NTUA tip leakage annular cascade

This fundamental experiment has recently been conducted by NTUA (National Technical University of Athens) within a collaborative European project under the BRITE-EURAM program. A detailed description of the test facility is reported in [Mathioudakis et al, 1997]. This experiment is dedicated to the study of tip clearance effects in a high speed rotor configuration. As measurements within a rotating blade passage are difficult, a stationary blade with a rotor airfoil has been designed with an inner wall rotating from pressure to suction sides. It thus simulates the flow at the tip of a rotor at the rear of an axial high pressure compressor where the clearance effect impacts the most the structure of the flow. As shown in figure 5, the cascade inlet swirl is created by a scroll through which the air is sucked by means of an axial compressor placed downstream of the cascade. The flowpath is cylindrical and the blades are straight. Two values of tip clearance have been tested : 2% and 4% of blade height.

4.1.2 CME2 subsonic stage

This laboratory compressor stage was designed in 1995 by SNECMA to be representative of the unsteady rotor/stator interaction encountered in modern high pressure multi-stage compressors. The originality of the design (Figure 6) is that the compressor geometry has been specifically tailored to ease the instrumentation problems: simple blade geometry; cylindrical casing; large dimensions. As a result, this compressor stage features an aspect ratio and Mach numbers typical of rear stages while the blade height and hub-to-tip ratio are more representative of front stages. The CME2 stage is currently being tested at the LEMFI test facility within the « Forced response project », in parallel to the development of the unsteady Navier-Stokes TURBO3D solver.

4.1.2 ECL4 transonic stage

In the early nineties, SNECMA designed this transonic compressor stage to be representative of the first stage of a high pressure-ratio HP military compressor that would be characterized by a reduced number of stages while maintaining moderate tip speeds. This design choice naturally led to an extremely high aerodynamic loading which positions the ECL4 stage among the most highly loaded machines known to the authors. This research compressor was first tested at the 2MW test facility of Ecole Centrale Lyon in 1994. Details on the ECL4 experiments are given in [Escuret et al, 1997]. The ECL4 flowpath is represented on figure 7.

4.2 Technological effects

Turbomachinery components are characterized by a wide range of technological features which have, to some extent, an interaction with the mainstream flow. The most obvious technological effect is the required radial clearance between stationary and rotating parts which gives rise to leakage flows for both rotors and stators (hub clearance or shroud seal leakage). These effects can also include bleed flows, blockage due to fillet radii and instrumentation as well as disturbances associated with rough, eroded, discontinuous or non-uniform surfaces. Overall, these technological effects can introduce a significant performance departure from the ideal (i.e. minimum loss) blade and flowpath geometry.

Two technological effects illustrated by both experimental and numerical results are presented in this paper. These results show a significant impact of technological effects on compressor performance and the interest of using CFD tools for the simulation of these effects :

- tip clearance effect in the NTUA annular cascade
- effect of a mismatch between the buttons of variable-stagger stator vanes and the flowpath in the ECL4 stage

4.2.1 Tip clearance effects

Solutions of the three-dimensional Navier-Stokes equations were obtained from the TURBO3D code on the two clearance NTUA test cases using fine grids (between 1.4 and 1.5 million mesh points). Figure 8 shows the computed development of the tip clearance vortex along the chord in the gap region.

A detailed analysis of the tip clearance effect and comparisons of experimental and numerical results can be found in [Bonhommet et al, 1998]. The main conclusions of this study are :

- The rolling-up of the leakage flow into a vortex approximately corresponds to the location of the minimum static pressure on the blade suction surface. Moreover, the tip clearance vortex is able to substantially alter the static pressure field near the blade tip on the suction side, moving the minimum pressure back along the chord as the clearance is increased.

- The leakage vortex is responsible for a substantial total pressure loss on 30% of blade span, a large underturning of the flow near the rotating hub and a flow overturning at around 20% of blade height (Figure 9).
- The comparison of computational and experimental results shows fair agreement : the code gives an accurate prediction of the clearance loss but tends to overestimate the tip clearance effects on flow angles. This last discrepancy is attributed to the limitations of the turbulence model to correctly predict the complex flow within the leakage vortex. Improvement of the model should include both an advanced ε-equation (taking into account the departure of turbulence from equilibrium) and a closure taking into account the Reynolds stress tensor anisotropy.

4.2.2 Effect of a mismatch between the buttons of variable-stagger stator vanes (VSV) and the flowpath

The first tests of the ECL4 transonic compressor stage carried-out in 1994 at the Ecole Centrale Lyon test facility demonstrated a very good overall compressor performance. Moreover, the traverses performed behind the rotor showed a satisfactory flow behavior and were found to be in good agreement with the results of 3D Navier-Stokes « CANARI » simulations. However, the measurements obtained behind the stator vanes revealed some unexpected details of the flowfield.

As shown on figure 10 a region of high pressure losses can be identified behind the stator vanes on a substantial portion of the annulus toward the outer annulus. This corner flow separation could not be reproduced by 3D Navier-Stokes computations of the stator vanes. Following the test results, a close examination of the ECL4 geometry revealed that the buttons of the variable stator vanes were slightly out of line with the flowpath, by a value of about 0.3 mm which amounts to 0.5% of vane height (Figure 11).

As detailed in [Escuret et al, 1997], using a simple numerical approach to account for the actual geometric discontinuity of the annulus, the « CANARI » computation then showed flow trends similar to that of the experiment. Also, a detailed analysis of the computed flow field indicated that the flow turning (in both the radial and tangential directions) due to the button blockage contributed toward strengthening the effect of secondary flows. Subsequently, after the geometry of the VSV buttons was corrected to match the flowpath, further tests confirmed a much more satisfactory flow behavior leading to a one-point improvement in overall compressor isentropic efficiency.

This study leads to the conclusion that ensuring a smooth flowpath can be critically important for the high stage loadings characteristic of advanced military applications. Moreover, the predictive value of 3D Navier-Stokes computations for the simulation of technological effects, such as VSV buttons / flowpath mismatch, is clearly demonstrated.

4.3 Multiple blade row calculations

With the recent increase in computational power, the compressor designer is no longer restricted to the analysis of an isolated blade row when using 3D Navier-Stokes computations. It is now possible to consider multiple blade row configurations to take into account the influence of adjacent blade rows (Liamis, 1998) and to predict the development of endwall losses across the compressor, provided that some simplifying assumptions are made so as to perform a steady computation.

Two different approaches currently used at SNECMA for the coupling of blade rows are presented in this paper:

- the **mixing plane** approach
- the **deterministic stress** approach

4.3.1 Mixing plane approach

In this simple approach, the tangential averages (in the stationary frame of reference) of flow quantities at one side of the interface plane between adjacent blade rows are used to update the numerical scheme values on the other side of the interface plane. The precise choice of the physical flow properties to be averaged and exchanged across the interface plane is not a trivial matter as there is no such average flow that would satisfy all the conservation equations at the same time. A simple solution is to use primitive flow variables, replacing the internal energy by the static pressure : ρ, ρV_x, ρV_r, ρV_t, p, k, ε. Another widely used approach is to use conservative flow variables, i.e. ρV_x, ρV_x+p, ρV_xV_r, ρV_xV_t, ρV_xH. A third approach is to favor the continuity of the entropy flux over that of ρV_x+p. Whatever solution is used, a natural effect of the mixing plane approach is that the average of some physical flow properties are discontinuous across the interface plane between adjacent bladerows.

Figure 12 shows the flowfield computed by the TURBO3D code on the full ECL4 compressor stage (i.e. including the inlet guide vanes, the rotor blades with tip clearance and the stator vanes) using a mixing plane approach with the conservation of primitive variables across interface planes. As shown on the compressor map of Figure 13, a good quantitative agreement is achieved between the measured and computed performance of this highly loaded transonic compressor stage near design conditions.

4.3.2 Deterministic stress approach

The « mixing plane » approach is easy to code and computationally efficient. However, it assumes that the flow quantities to be transferred across to the adjacent blade-rows instantaneously mix-out across the interface plane to give a tangentially uniform flow. Obviously, this is far from the real situation for which wakes, shock wave and potential flow disturbances originating from one blade row interact through a complex unsteady mechanism with the neighboring blade rows.

An approach first exposed by [Adamczyk, 1985] proposes to account for the « average » contribution of the temporal and passage-to-passage flow perturbations in a steady, periodic from blade passage to blade passage, multi-stage flow model : the so-called « average-passage » flow equation system. Although the derivation of this model is mathematically rigorous, its interest is practically limited by the difficult task of estimating the new terms in the equation system, i.e. the « deterministic stresses ».

A simplified approach proposed by [Rhie, 1995] neglects the passage-to-passage flow variations and calculates the values of the deterministic stress terms using a steady representation of blade row interaction. This approach has recently been introduced in the CANARI code under a collaborative research project with Ecole Centrale Lyon, ONERA, TURBOMECA and SNECMA. As illustrated on Figure 14 for the case of the CME2 subsonic compressor stage, the deterministic stresses are calculated using spatial (i.e.

tangential) averages on overlapping meshes where axi-symmetric bodyforces have been applied to account for the potential effect between closely coupled rows. During the computation, both the deterministic stress terms and the body forces are exchanged from one blade computational domain to the other.

Although it is more CPU expensive than the mixing plane approach, this approach presents some valuable advantages. It is a continuous interface plane approach as, by definition, the contribution of deterministic stresses restores the continuity of tangentially-averaged flow properties across interface planes. Moreover, it simulates the average wake blockage and the steady mixing effects which are believed to be of primary importance for the matching of blade rows at off-design conditions. However, purely unsteady effects such as wake or shock wave chopping by neighboring blade rows (i.e. unsteady mixing effects) are clearly neglected.

5. UNSTEADY ANALYSIS

The flow in aero-engine compressors is fundamentally unsteady, given that energy transfer between rotating blade rows and the flow is basically an unsteady phenomenon. The influence of flow unsteadiness on compressor aerodynamic performance has been discussed in the previous section dealing with rotor/stator interaction. Rather, this section focuses on stability considerations linked to flow unsteadiness. These can be divided into three aspects. Two concern fluid/structure interaction : blade flutter and forced response. The third one deals with the aerodynamic instabilities of the compression system as a whole, namely stall and surge.

5.1 Blade flutter prediction

Blade flutter is a major problem for the safety of compressor operation. It comes from an unstable coupling between the blade vibration modes and the resulting flow unsteadiness. This potential problem is also well known on aircraft wings and helicopter blades. In aero-engine fans and compressors, this phenomenon can have several origins according to the operating conditions. With supersonic inlet conditions, flutter can be initiated by strong shock wave unsteadiness in the blade passage, this form of flutter being referred to **supersonic flutter**. At a lower rotational speed and high inlet angle of attack to the airfoils, an unstable flow separation occurring at the leading edge on the suction side can also be coupled with blade vibration and is referred to **subsonic flutter**. At high flow rate and low pressure ratio operating conditions, the instability may come from the choking of the blade passage, i.e. **choke flutter**.

5.1.1 Supersonic flutter

In the case of supersonic flutter, inviscid effects are considered preeminent, in so far as the unsteady component of static pressure on the blade surface (which is what puts work into the blade vibration) mainly depends on the oscillation of the strong shock wave in the blade passage. As a result, Euler computations are thought to be adequate to predict this form of flutter.

The analysis procedure is detailed in [Gerolymos, 1992a] and [Burgaud, 1996]. First, a structural vibration mode analysis is performed in running conditions, i.e. taking centrifugal forces and temperature effects into account. This mechanical analysis is carried-out on the whole bladed disk using cyclic symmetry, thus yielding the basic vibration mode frequencies and shapes for the various inter blade phase angles. The resulting blade surface displacement distribution for a given mode is used as an input to 3D Euler unsteady computations. The unsteady calculation is performed around the vibrating 3D blade, and a chorochronic periodicity technique allows the computation to be run on a single blade passage regardless of the azimutal wave number of the vibration mode [Gerolymos, 1992b]. For the common full titanium blades, it is found that the initial vibration mode does not need to be modified to account for the flow influence. In the case of composite or hollow titanium blades however, the aero-mechanical (i.e. coupled) mode can differ somewhat from the steady flow mechanical mode and it is necessary to update, in an iterative way, the vibration mode as the unsteady flow calculation progresses. The results of the 3D computation is then summarized in terms of the distribution of the mean power due to the unsteady pressure forces on the blade surface. This mean power distribution can be integrated over the blade surface to yield the aerodynamic damping parameter, i.e. a measure of the stability of fluid/structure coupling. This can be evaluated for several operating conditions and thus used to determine probable supersonic flutter zones on the compressor map.

This procedure has been validated on several civil and military engine fans. It is systematically used today in the fan design process, in order to anticipate a potential risk of supersonic flutter very early in the project.

To illustrate the interest and validity of the analysis, results obtained on both shrouded and wide-chord fan blades relative to the problem of supersonic flutter are presented. Figure 15 shows results of computations on a research wide chord fan : for the 3 modes analyzed, no instability is predicted as long as the rotor tip passage flow remains started (this corresponds to the part of the fan map where the corrected inlet mass flow is constant), and that is found to be in agreement with the experiment. The only instability predicted concerns the first flex mode (vibrating on a +2 nodal diameter pattern) for unstarted flow configurations. This typical « supersonic stalled flutter » was observed experimentally with the same mode pattern but closer to the surge line (Figure 16). The inaccurate location of the flutter zone is mainly due to the lack of precision of the 3D Euler method in predicting the fan steady-state performance at nominal speed.

Another application concerns a research transonic fan with part-span shrouds, which experienced supersonic flutter problems in an early phase of the research project. The analysis (Figure 17) indicates that some of the bladed disk modes (namely the second system mode vibrating in a 4, 5 and 6 nodal diameter forward traveling wave) become unstable below a given pressure ratio (at nominal speed), or above a given rotational speed (at a given back pressure). The experimentally observed flutter modes were the same as those predicted and the location of the flutter zone on the fan map was in good agreement with the analysis.

These results validate the assumption that supersonic flutter can be predicted by a 3D unsteady Euler analysis, provided that the full bladed disk modes are accurately calculated.

5.1.2 Subsonic flutter

Unlike supersonic flutter, subsonic flutter involves strong viscous effects as it is characterized by an unsteady separation of the boundary layer on the blade suction surface near the leading edge. In consequence, it requires the use of unsteady Navier-Stokes computations with a turbulence model appropriate to the simulation of this complex flow phenomenon.

The approach recently developed by SNECMA is based on a two equation k-ε turbulence model with a low Reynolds model near the wall. This approach is currently being validated against 2D cascade data representative of the tip section of a wide chord fan at part speed conditions (inlet Mach number of 0.7 and 6° positive incidence). Figure 18 shows the Mach number contours around the blade airfoil as computed by the 2D Navier-Stokes code with a k-ε turbulence model : a large flow separation initiates at the leading edge and extends over 10% of the airfoil chord on the suction surface. The real and imaginary parts of the unsteady static pressure coefficients on the airfoil suction and pressure sides are given in Figure 19 (case of a torsion mode at the frequency of 332Hz and phase angle of 90°).

The current approach taken by SNECMA is to use this newly developed numerical analysis in support of the available empirical criteria as the validity of these criteria is generally limited to the range of existing configurations.

5.2 Forced response analysis

Another source of fluid/structure interaction is the rotor/stator aerodynamic interaction. Each blade row is periodically impinged by the wakes coming from the upstream blade row(s) and submitted to potential or shock wave interactions from the downstream blade row(s). The usual procedure in blade and vane design consists in avoiding too close proximity between the frequencies of blade or vane vibrating modes and the forced excitation frequencies linked to upstream and downstream blade rows, for rotation speeds corresponding to steady engine operation. This procedure is typically illustrated by the Campbell diagram representation.

In the case of most multi-stage compressors, however, it is next to impossible to avoid all crossings with the required frequency margin. The designer has therefore to make a choice between several non ideal configurations, mainly on the basis of prior empirical experience. But this is sometimes inconclusive or simply scarce. The approach developed at SNECMA is to provide help to the aero-mechanical designers in assessing how critical the potential frequency crossings are, by using unsteady computations [Berthillier et al, 1994].

The first important piece of information is the aerodynamic damping of the vibration mode concerned by the interaction, at the rotation speed at which the frequency crossing occurs (and, say on the compressor operating line). Considering that the flow on the operating line is not too far off-design, the aerodynamic damping is determined using the same 3D Euler code as that used for supersonic flutter studies.

The aerodynamic damping would probably be enough to choose between configurations but does not ascertain that any of the configuration of the blade forced response is in fact acceptable, i.e. that the dynamic stress levels on the blade are within the material strength characteristics. This requires the computation of the blade forced response, which implies knowing the aerodynamic forcing function. As mentioned before, the origin of aerodynamic forcing can be potential (an effect which propagates upstream and downstream according to pressure waves), vortical (an effect which only propagates downstream by convection of the upstream airfoil wakes) or associated with a shock wave (originating from the leading edge of a downstream airfoil in the compressor). Shock wave interaction is typically found as the main interaction between the first rotor and the inlet guide vanes of a multi-stage compressor (Figure 20). Potential and shock wave interactions are treated at SNECMA using a full stage, 3D rotor/stator Euler computation, as the flow phenomena involved are basically inviscid. Concerning vortical (i.e. blade/wake) interaction, the same 3D unsteady Euler code as for supersonic flutter is used, with vorticity (in the form of total pressure distributions) prescribed at the inlet of the computational domain. This data is obtained from a steady 3D Navier-Stokes computation of the flow around the upstream blade row.

At present time, aeroelastic analyses are conducted with tuned mechanical models, i.e. all the blades in a given row are assumed to have similar modes in frequency and shape. However, the effect of structural non-uniformities between blades is real and a small amount of mistuning can change the dynamic response of a bladed row by breaking the cyclic symmetry of the otherwise « organized » traveling modes. A simple approach was recently developed at SNECMA to try to quantify the amplitude magnification factor due to mistuning. A typical result of these analyses is given in Figure 21 where the forced response functions of several fan blades are plotted for a tuned and mistuned rotor (case of fan blade forced response due to inlet distortion).

The mechanical damping is also difficult to model precisely. The friction damping is present at the root of the blades, where they are in contact with the disk. Usually, a modal damping model is used. The values, generally small, i.e. <1%, are determined experimentally. Specific friction damping devices may also be used under the blade platforms. In this case, an optimum damper can be found by specific analyses described in [Berthillier, 1995]

5.3 Compression system stability

In recent years, a large amount of work has been devoted to understanding the onset of stall and surge in axial multistage compressors. SNECMA actively took part in this research effort through a European collaborative project under the Brite-Euram program, in which four high speed compressors were tested to investigate the generic features of stall inception [Escuret, 1995; Day et al, 1997]. The measurements showed a very broad range of stall related disturbances. Both short lengthscale (spikes) and long lengthscale (modes) disturbances were detected in three out of the four compressors tested. A clear trend was observed with spikes appearing at low rotational speeds changing to modes in the mid-speed range (i.e. 80%-90% of nominal speed). Moreover, stage matching was identified as one of the parameters which can bring about a change from one stalling pattern to the other [Camp, 1997]. Spike type stalling, a localized phenomenon, would seem to result from situations where individual blade rows are more highly loaded than the rest while modal type stall inception, a more global phenomenon, would rather occur when all stages are evenly matched at the stall onset point. At full speed, the growth of the stall cells was found to take place over fewer rotor revolutions than at lower operating speeds and the origins of the stall cells were not clearly identifiable in terms of modes and spikes. In the compressor with the highest pressure ratio, flow breakdown at full speed occurred so quickly that rotating stall could not be detected before the surge event. The symmetry of the flow throughout the entire compressor was disrupted in the space of one rotor revolution.

Regarding the problem of aerodynamic instabilities, the compressor designer is faced with the practically important but difficult task of quantitatively predicting the surge line. Until recently, this was performed by using exclusively empirical criteria on parameters such as diffusion factors, flow incidence on blades or static pressure rise on the endwalls, all obtained from an off-design throughflow calculation. Nowadays, the trend is to rely on new methods more representative of the flow physics but a numerical method capable of predicting the surge line on the basis of a theoretical model must include several features. Firstly, it must take into account the whole compression system, i.e. all parts involved in the compressor stability : the compressor itself, the downstream volume and the throttling device which controls the operating condition of the compressor. Secondly, boundary layer growth and separation on the compressor blades and endwalls must be modeled in a way which permits to accurately predict the compressor speedline at off-design conditions (in this point generally lies the accuracy of the method). Finally, it has to be an unsteady method in order to adequately reproduce the onset of the unstable phenomenon.

The simplest level of modeling which fits this description is a time-linearised method, with 1D fluid equations integrated over cells each comprising a blade row or a full stage [Escuret, 1993]. Fluid perturbations in the compressor are then solutions of a linear system, the eigenvalues of which represent the damping or growth and frequency of these perturbations. Such a method is currently in use at SNECMA, integrated with a throughflow method to provide fast and reliable surge line predictions for HP compressors.

However, the method mentioned above is not adequate to deal with low hub-to-tip ratio machines or ones with strong flowpath curvature and radial variations. Moreover, it does not properly address the stall inception process in so far as it only accounts for axial instability modes (i.e. surge). A non-linear three dimensional method has therefore been developed at SNECMA [Escuret, 1994 & 1996] in order to simulate circumferential instability modes (i.e. rotating stall) as well as the non-linear coupling which is experimentally observed between rotating stall and surge. This method is based on a 3D unsteady Euler solution in blade free volumes which is dynamically coupled with a multiple through flow solution within blade rows (Figure 22). The blade row model is obtained from circumferentially averaged unsteady Euler equations so that blade effects are represented by two blade forces which are respectively perpendicular and parallel to the flow velocity. These blade terms are derived from steady-state blade row characteristics with a time lag approach (i.e. convection time) which considers the time required by boundary layers around blade profiles to adapt to varying inlet flow conditions. This code is capable of simulating the onset of long length scale rotating stall and is used to give a 3D picture of stall inception. Applied to a high speed four stage research compressor [Escuret, 1995], the method reproduces well the time scales characteristic of instability development. In particular, it simulates the fast growth rate of instability at full speed, giving rise to a global compressor instability in less than 5 rotor revolutions (Figure 23).

The 3D stall model only accounts for blade passage effects at a macroscopic level through the use of loss and deviation correlations. As a result, it cannot reproduce the development of spike-type stall, an instability for which the actual flow phenomena within the blade passage (i.e. large flow separation, tip leakage) must be resolved [Escuret, 1995]. This requires the use of unsteady 3D Navier-Stokes computations on numerous blade passages with a turbulence model capable of representing these complex flow phenomena. Although very consuming of computer power, this advanced numerical approach will soon be feasible, at least for single stage configurations.

6. CONCLUSIONS

This paper has presented the latest advances in the aerodynamic design and analysis process of fans and compressors at SNECMA. The main conclusions of the paper can be summarized as follows :

- The role of CFD in the design procedure is fast-growing. New tools have been developed allowing the treatment of numerous difficult problems as close as possible to the reality : tip clearance, technological effects, multistage effects, unsteady phenomena (forced response, aeroelastic and aerodynamic instabilities).
- A great effort is also dedicated to turn numerical methods into integrated tools which are easy to handle by designers. The aim is to create a « user friendly » environment to enable the designer to focus primarily on the physical analysis of numerical results.
- Experimental investigations of research compressors with a comprehensive and high quality set of measurements are essential to produce an appropriate database for the validation and calibration of advanced numerical methods.

The authors are strongly convinced that all these research efforts will provide a better understanding of the aerodynamic behavior of real aero-engine fans and multi-stage compressors. However, the integration of new analysis tools with improved simulation capabilities requires a permanent update of the design methodology in order to turn this knowledge into valuable gains to the final product.

It must be borne in mind that the ultimate objective of the design procedure is to improve the compressor performance and at the same time to reduce costs and design cycles. Despite the recent breakthrough in CFD, highly skilled engineers specializing in the field of compressor aerodynamics are therefore still needed in order to reach these ambitious objectives.

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It must be emphasized that the results presented in this paper have been obtained by many co-workers in the Department and at SNECMA.

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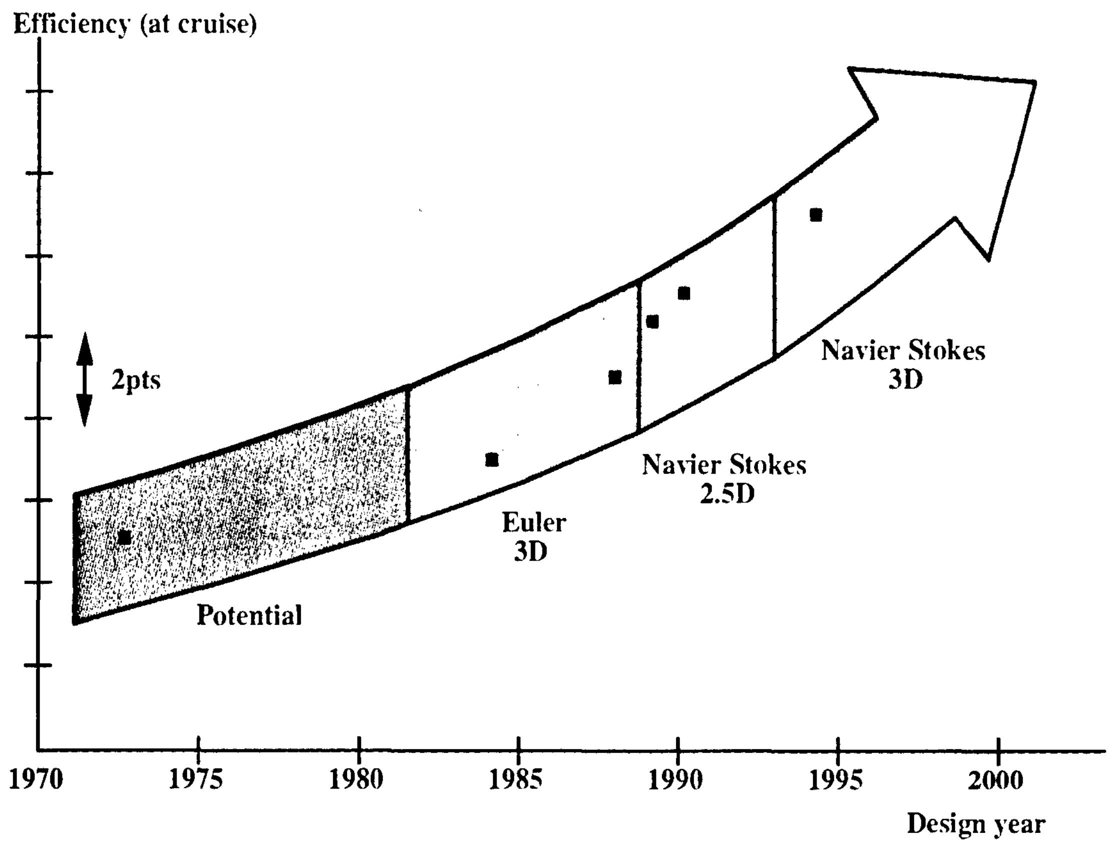


Fig. 1 Impact of CFD on SNECMA fan performance

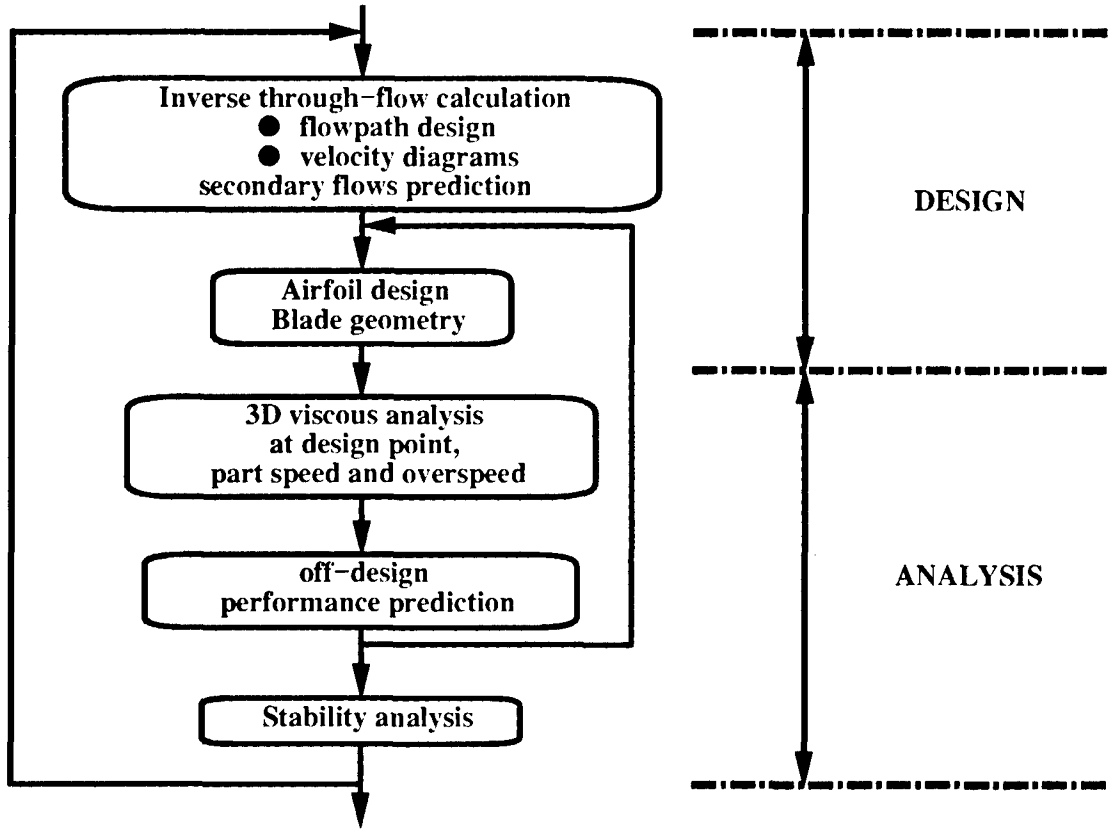


Fig. 2a Classical design procedure

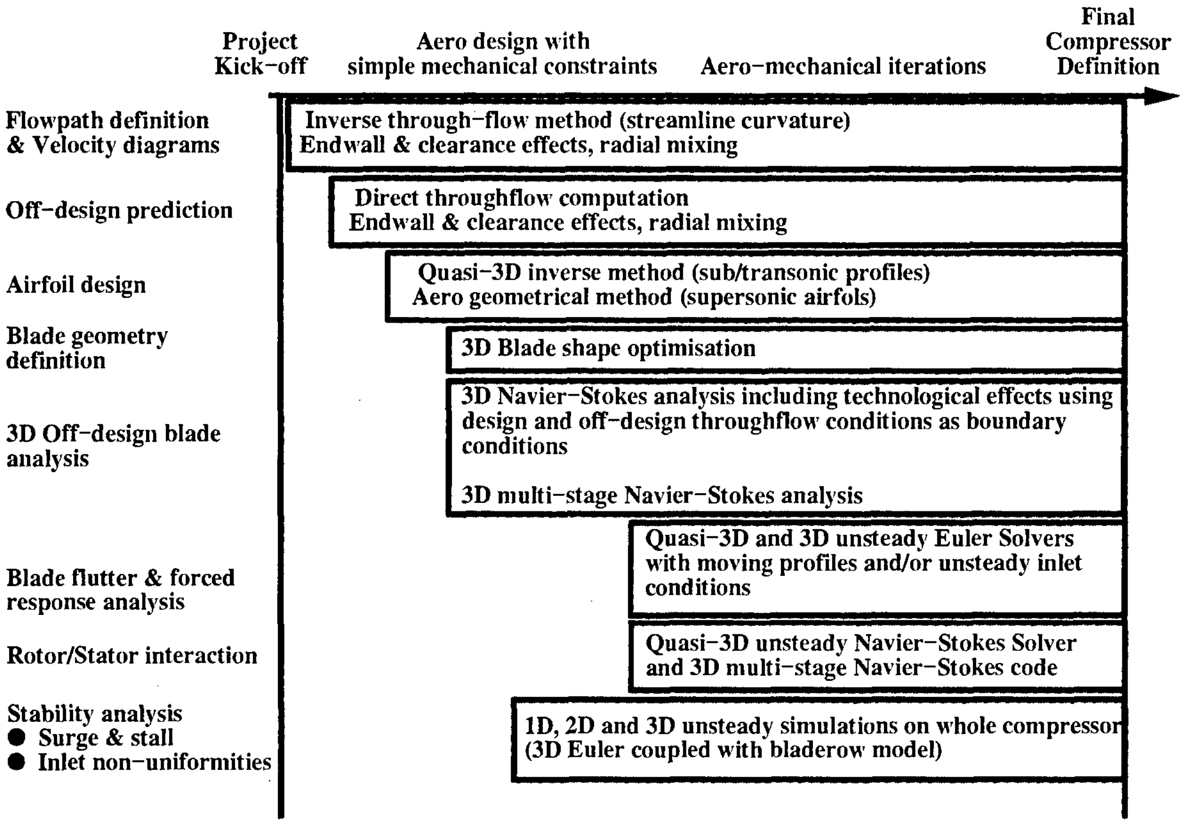


Fig. 2b Design procedure for highly loaded HP compressors

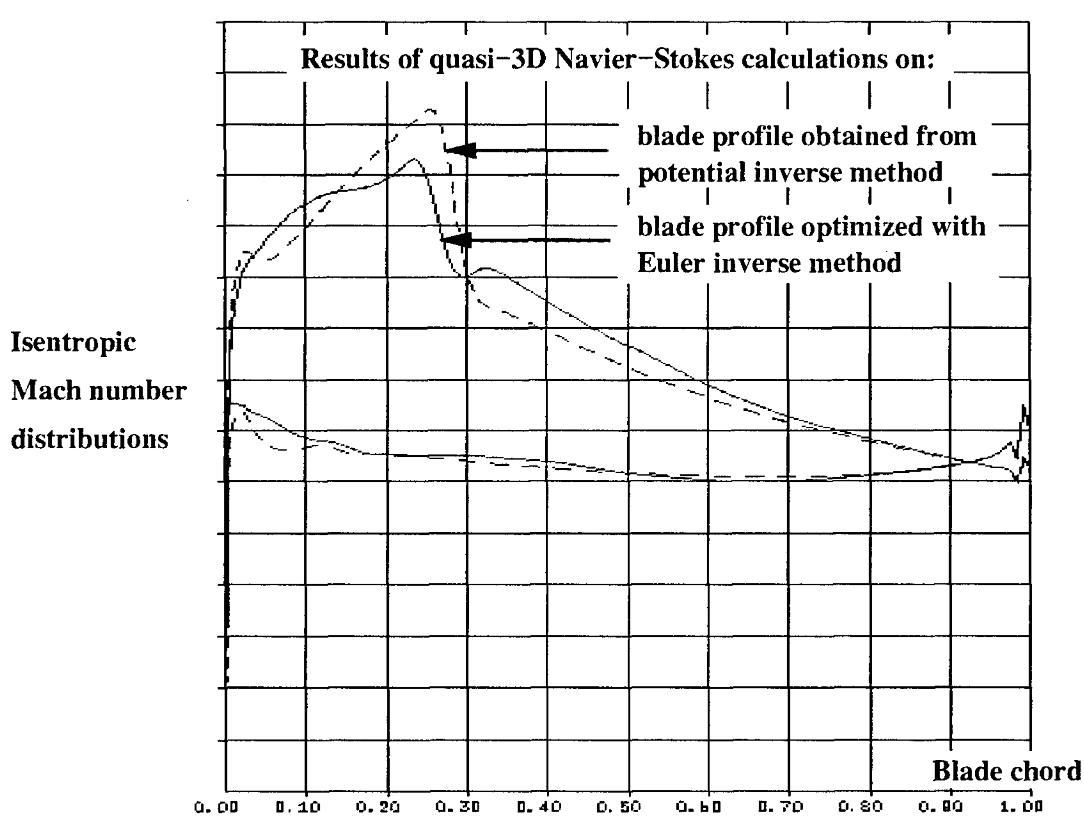


Fig. 3 Inverse methods

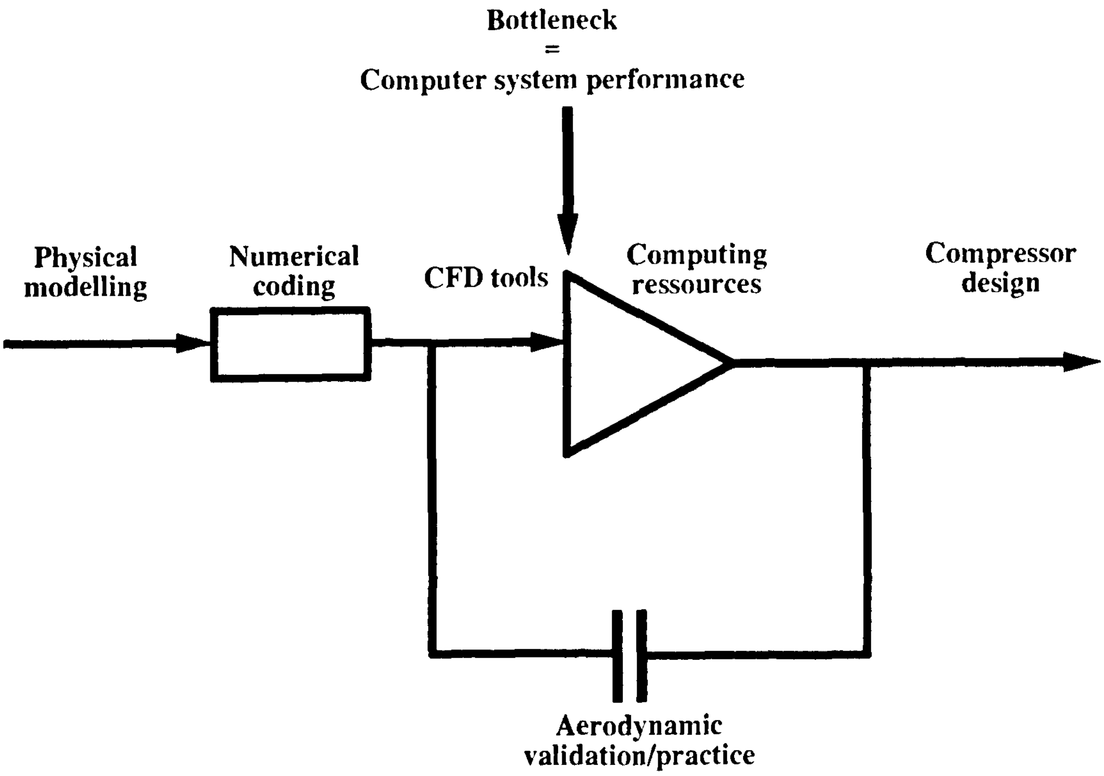


Fig. 4 Integrating CFD in compressor design

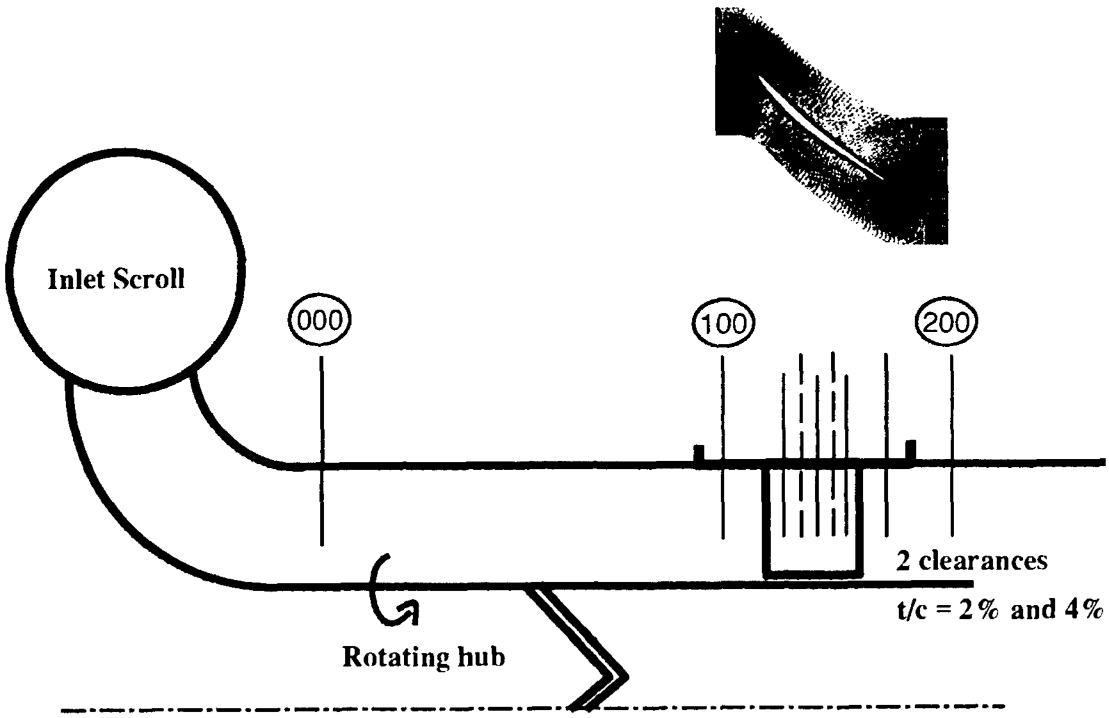


Fig. 5 Schematic of NTUA tip clearance annular cascade

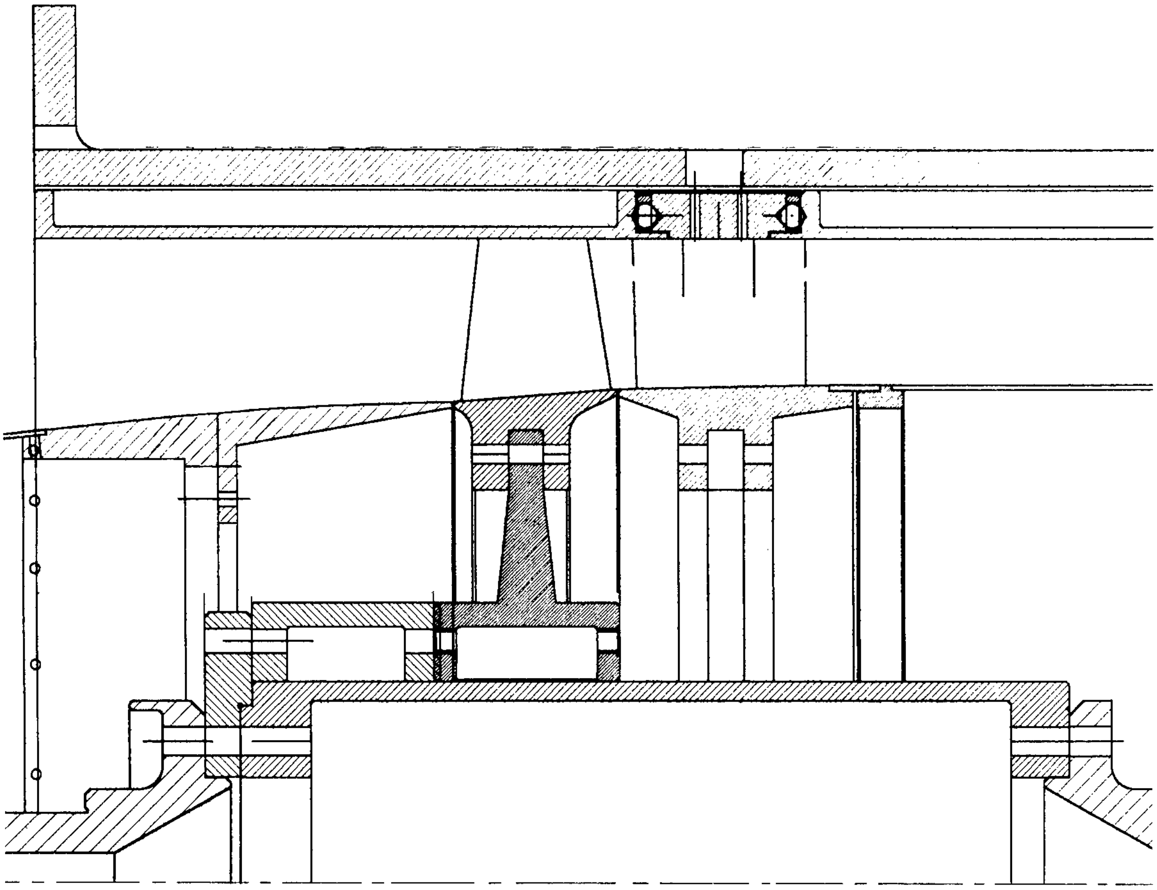


Fig. 6 Schematic of CME2 subsonic compressor stage

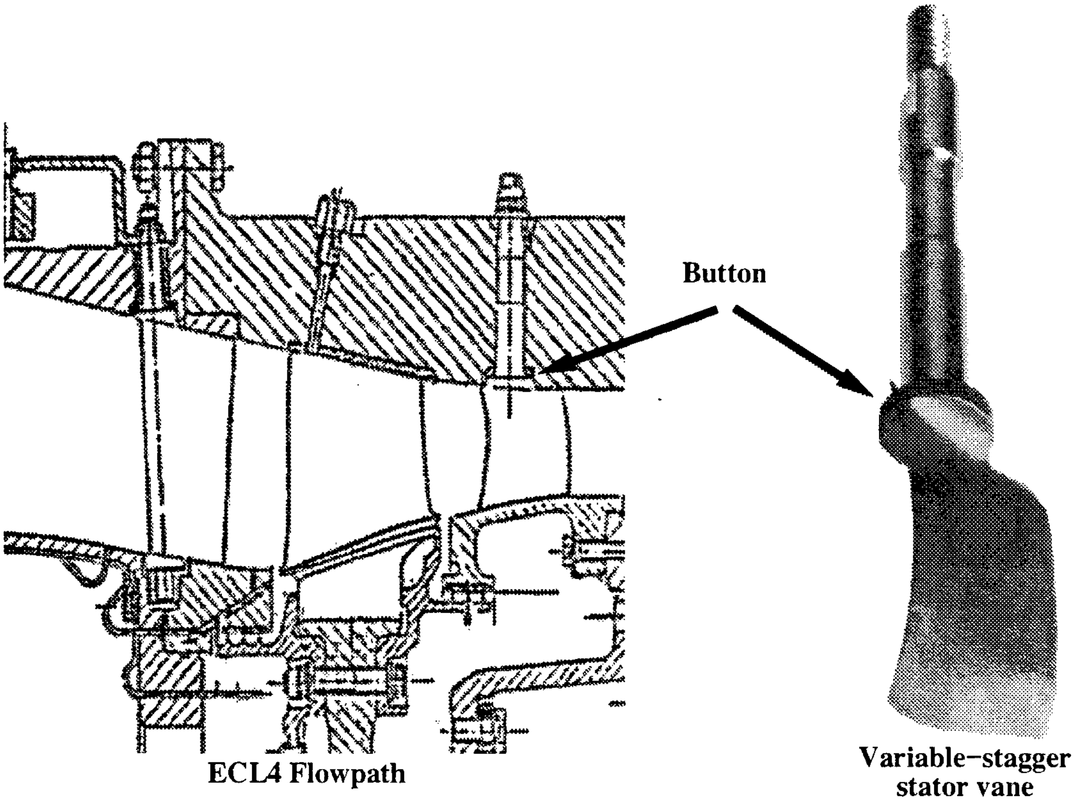


Fig. 7 ECL4 flowpath and VSV button

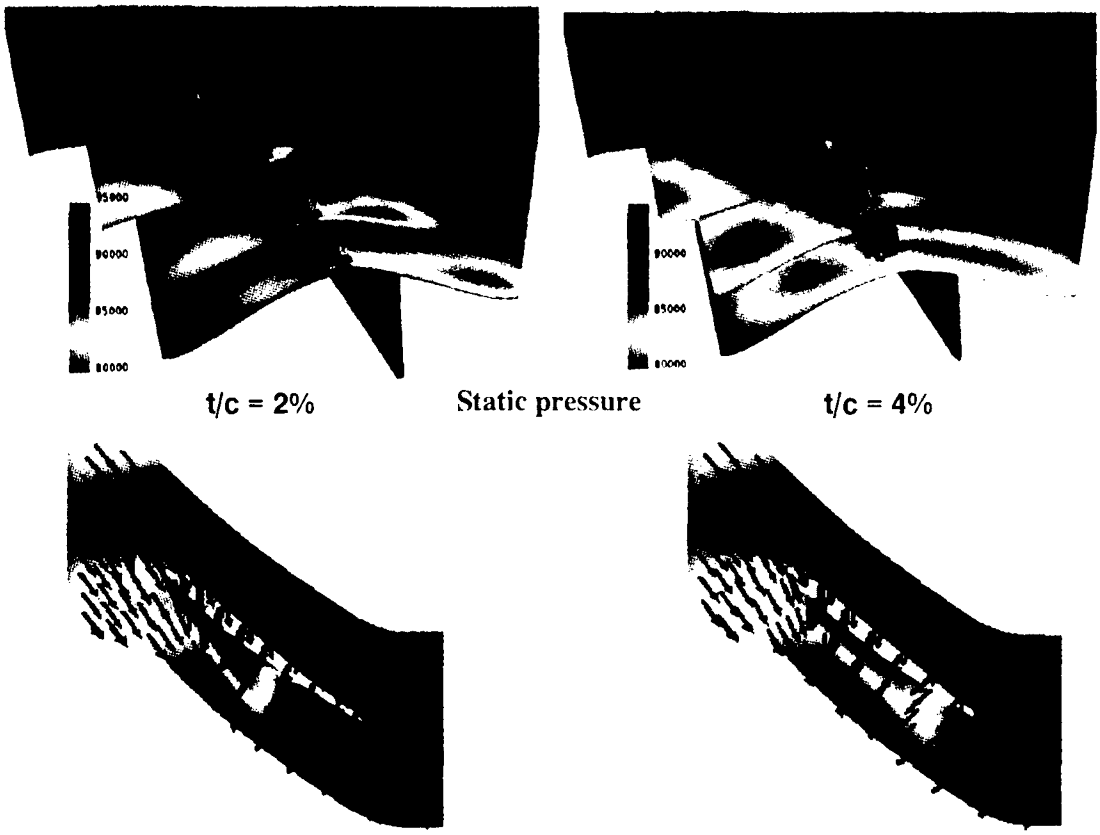


Fig. 8 Computation of tip clearance vortex (NTUA annular cascade)

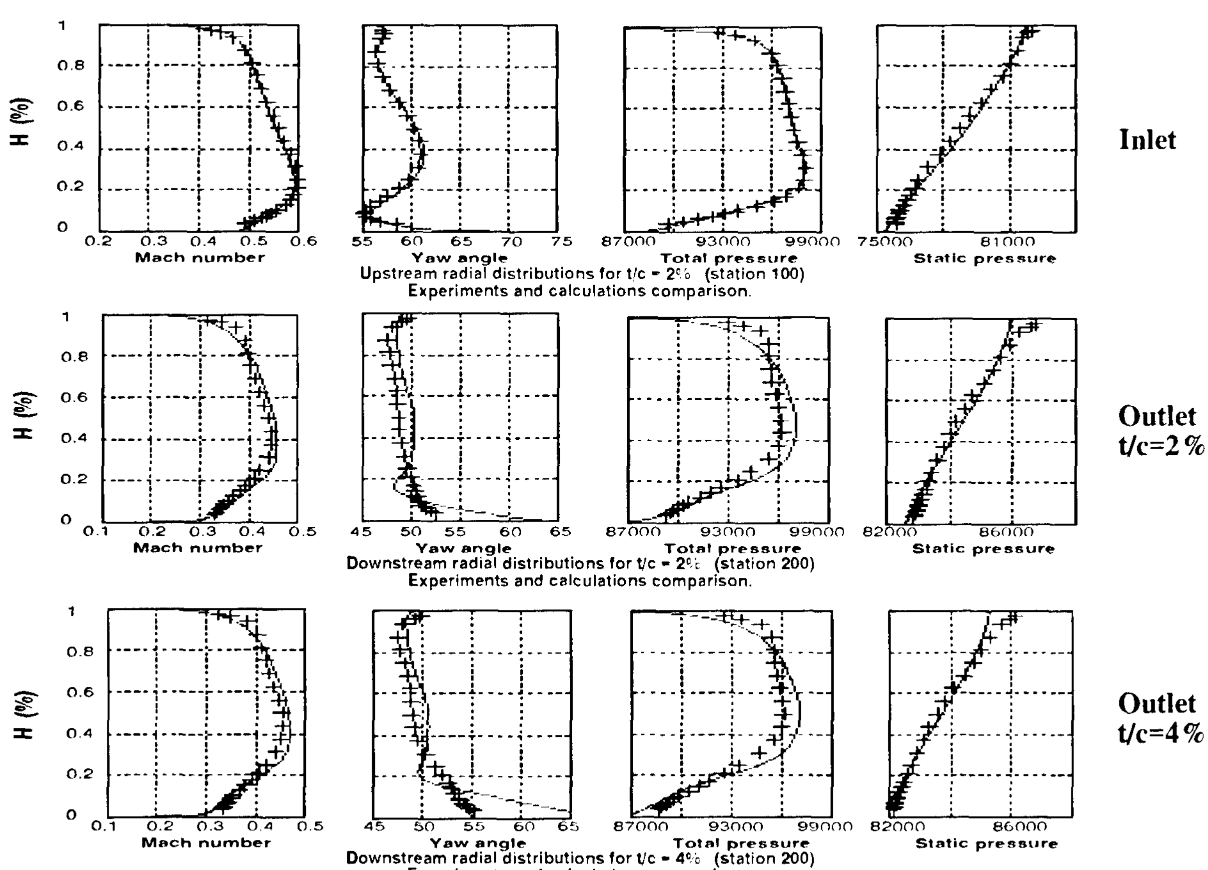


Fig. 9 Comparison of experimental and computed results (NTUA annular cascade)

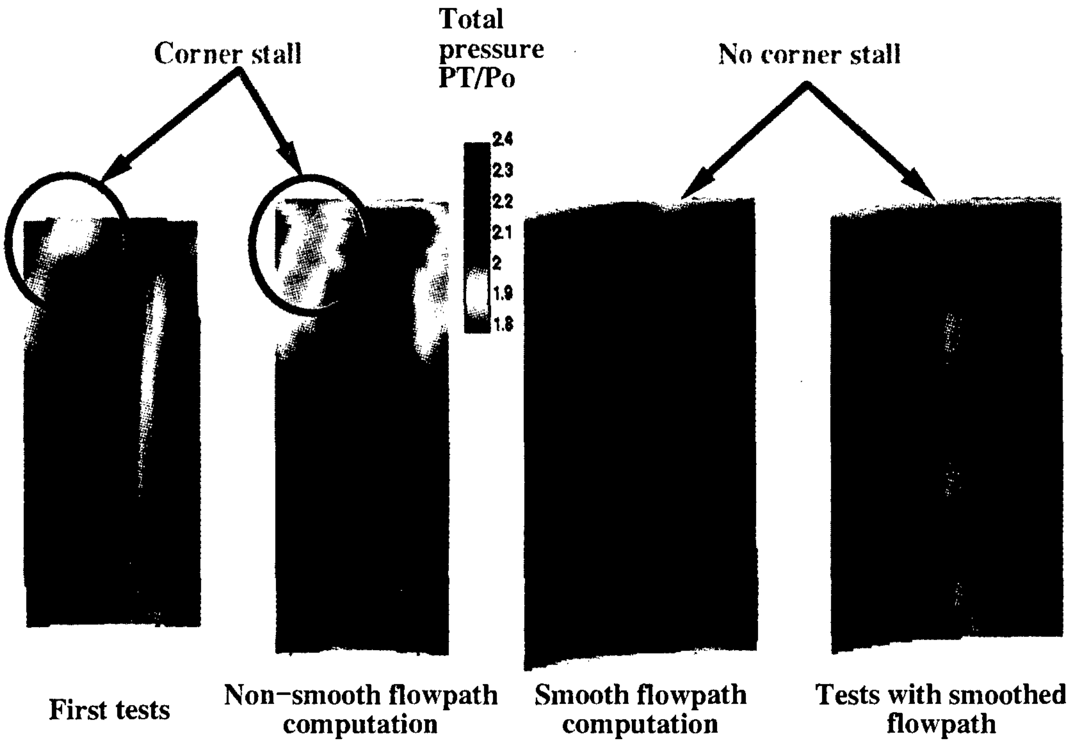


Fig. 10 Measured and computed absolute total pressure downstream of the ECL4 variable stator vanes

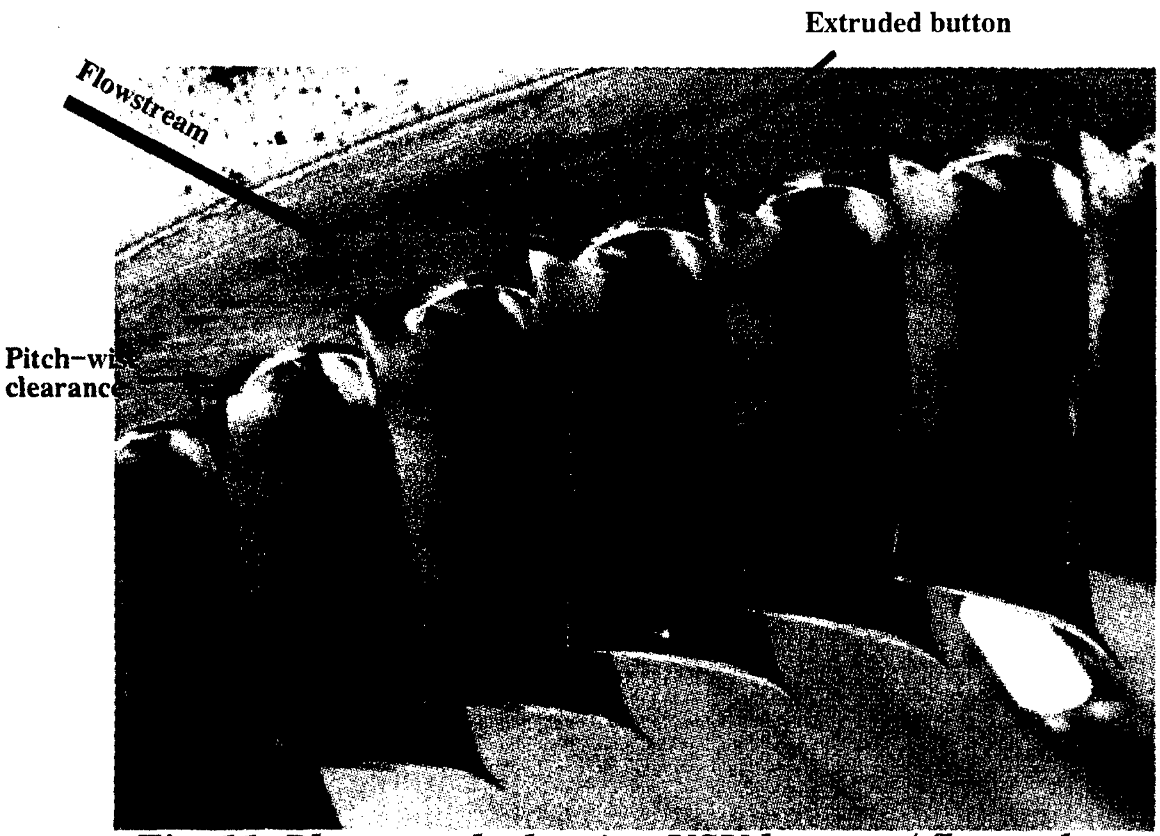


Fig. 11 Photograph showing VSV buttons / flowpath mismatch on ECL4 compressor stage

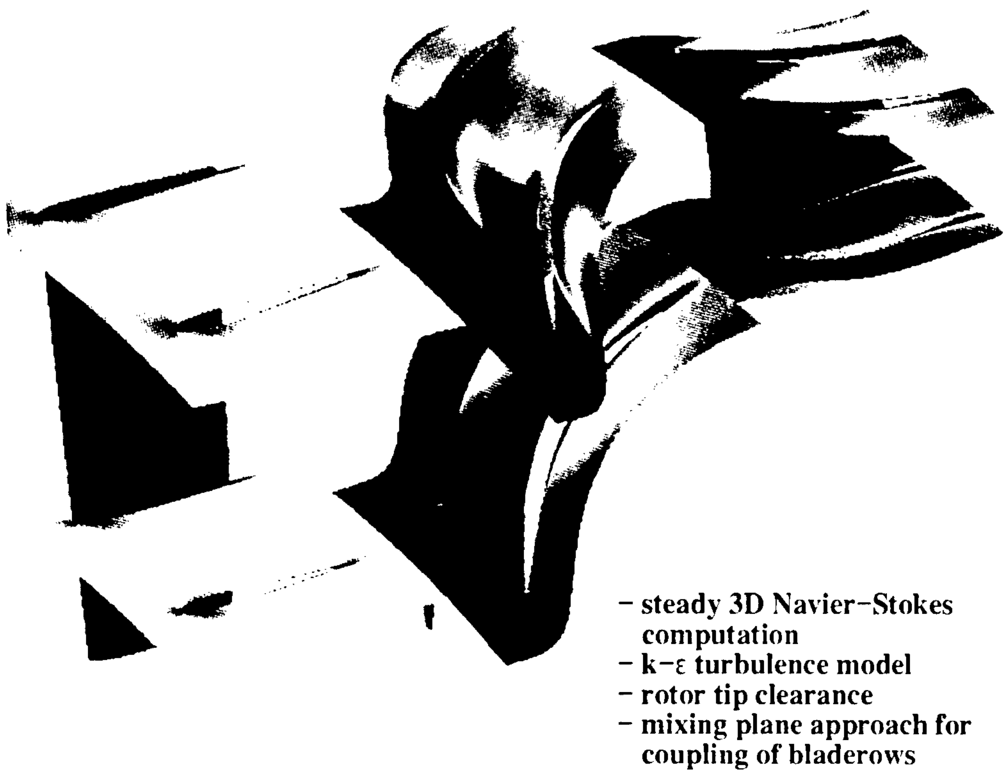


Fig. 12 Computation of ECL4 compressor stage

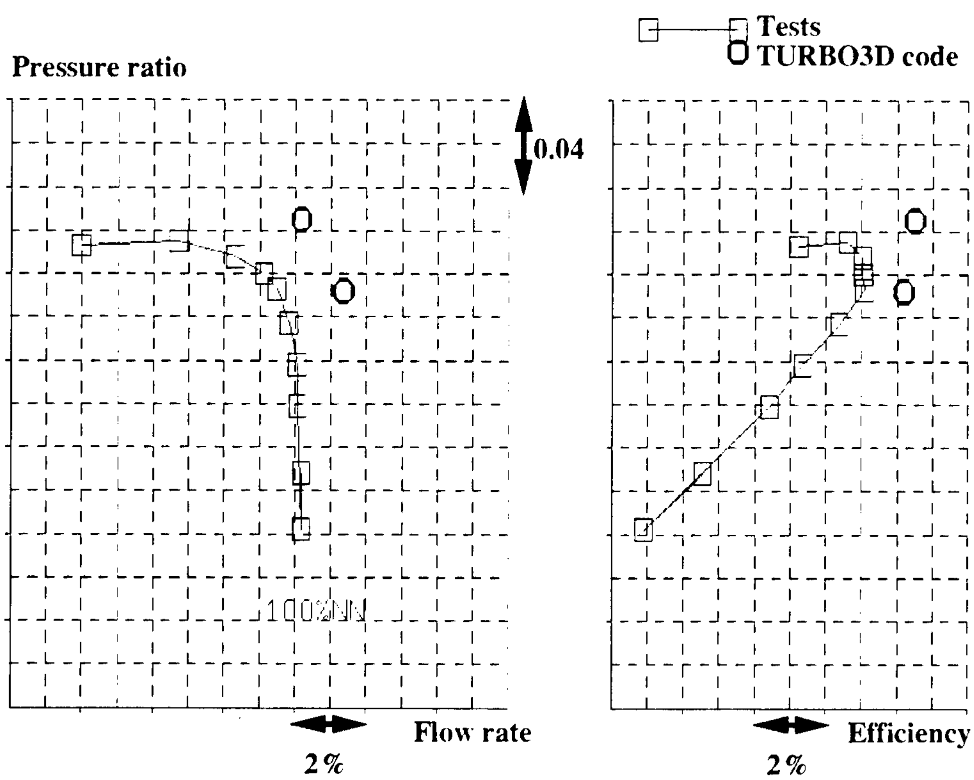


Fig. 13 Measured and computed compressor performance (ECL4 transonic compressor stage)

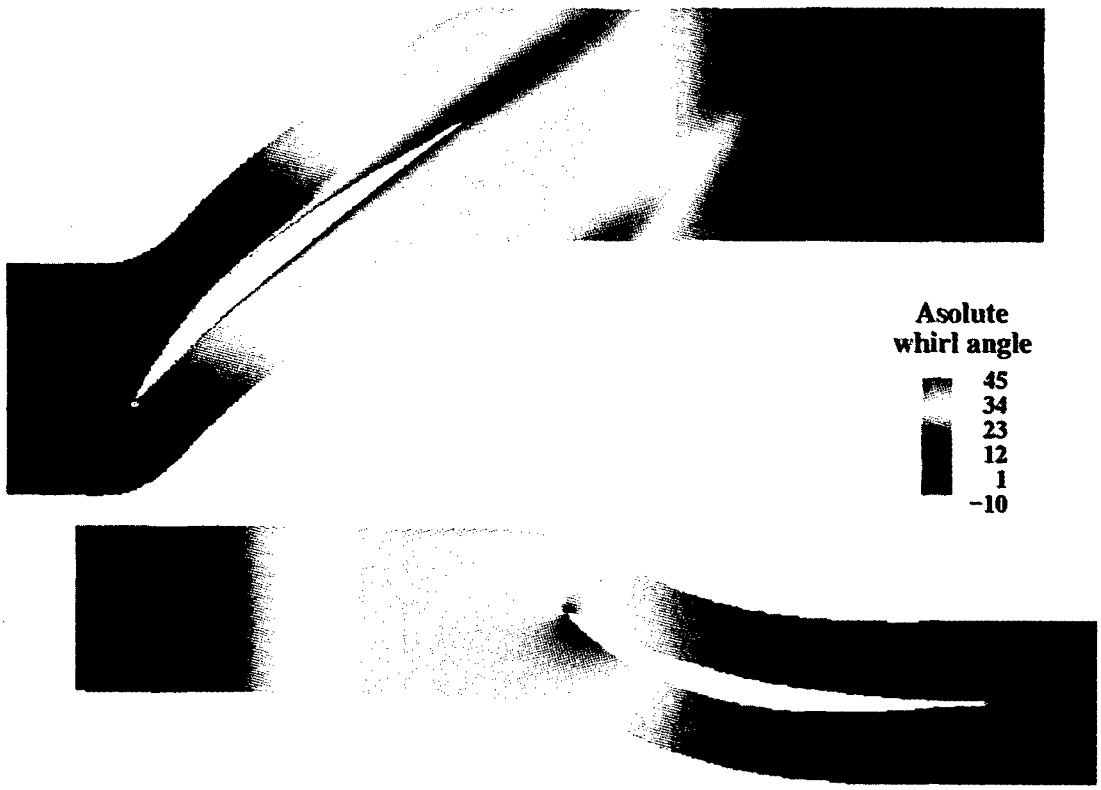


Fig. 14 Deterministic stress and body force approach (CME2 compressor stage)

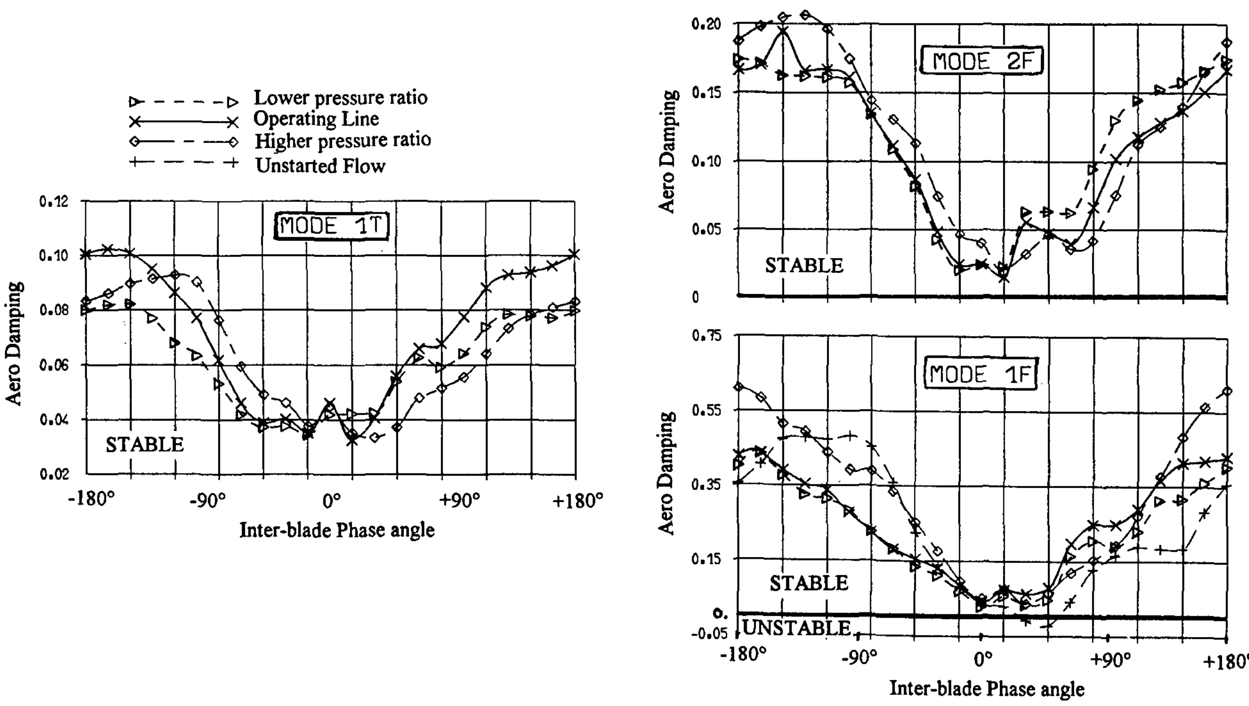


Fig. 15 Aerodynamic damping of 1F, 2F, 1T modes (3D EULER computations on research wide-chord fan)

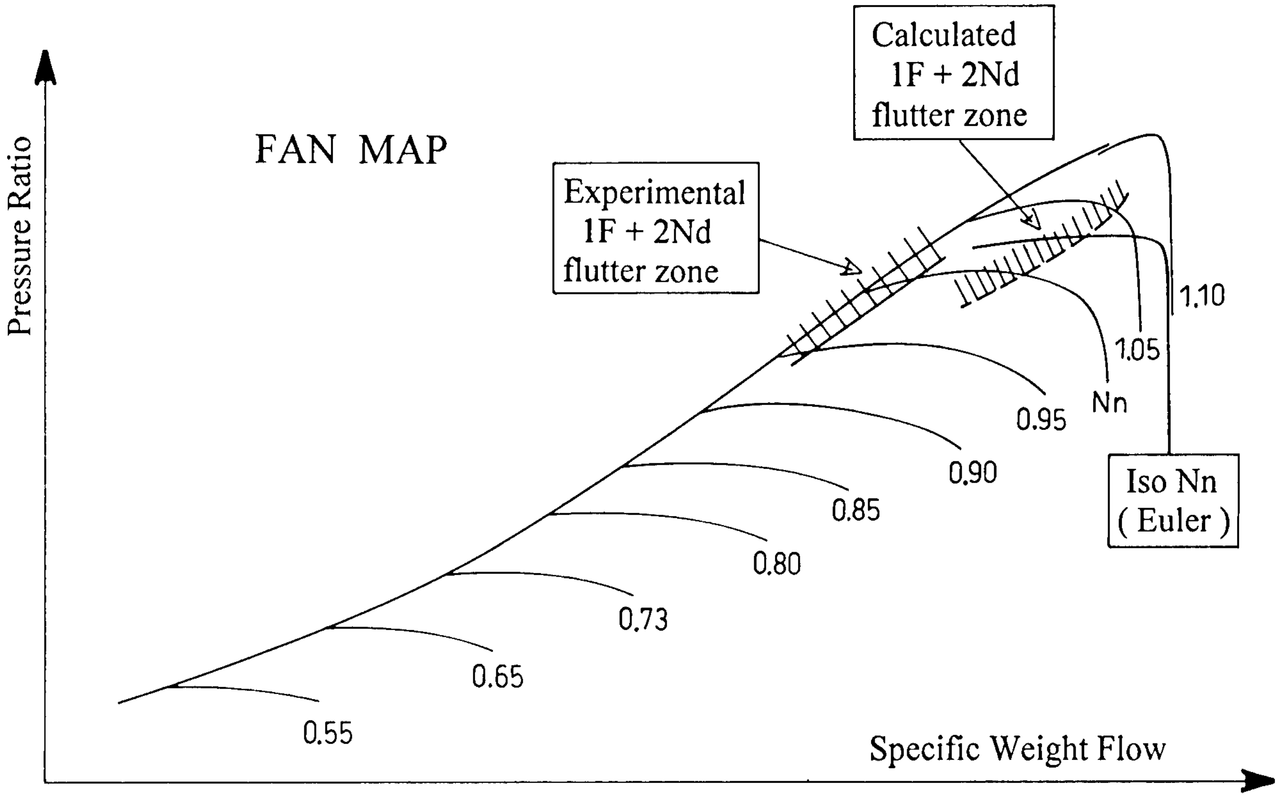


Fig. 16 Experimental & computed flutter limits (research wide–chord fan)

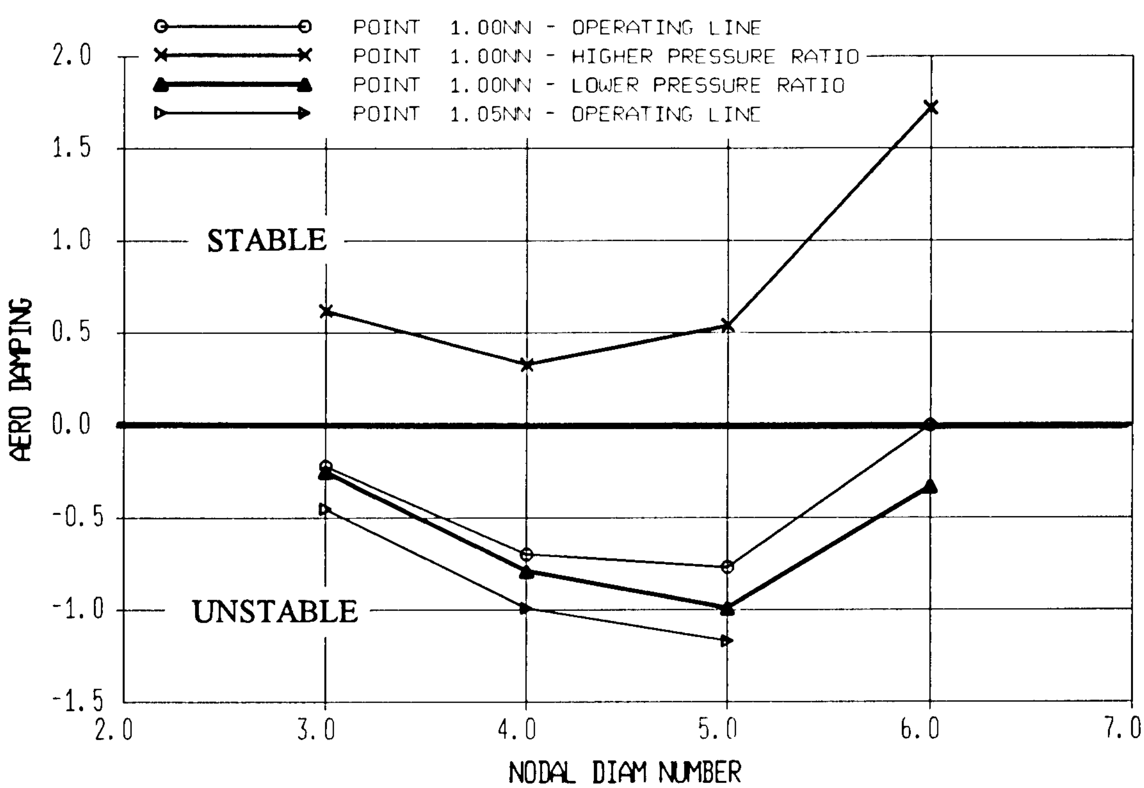


Fig. 17 Aerodynamic damping of 2nd system mode (3D EULER computations on part–span shrouded fan)

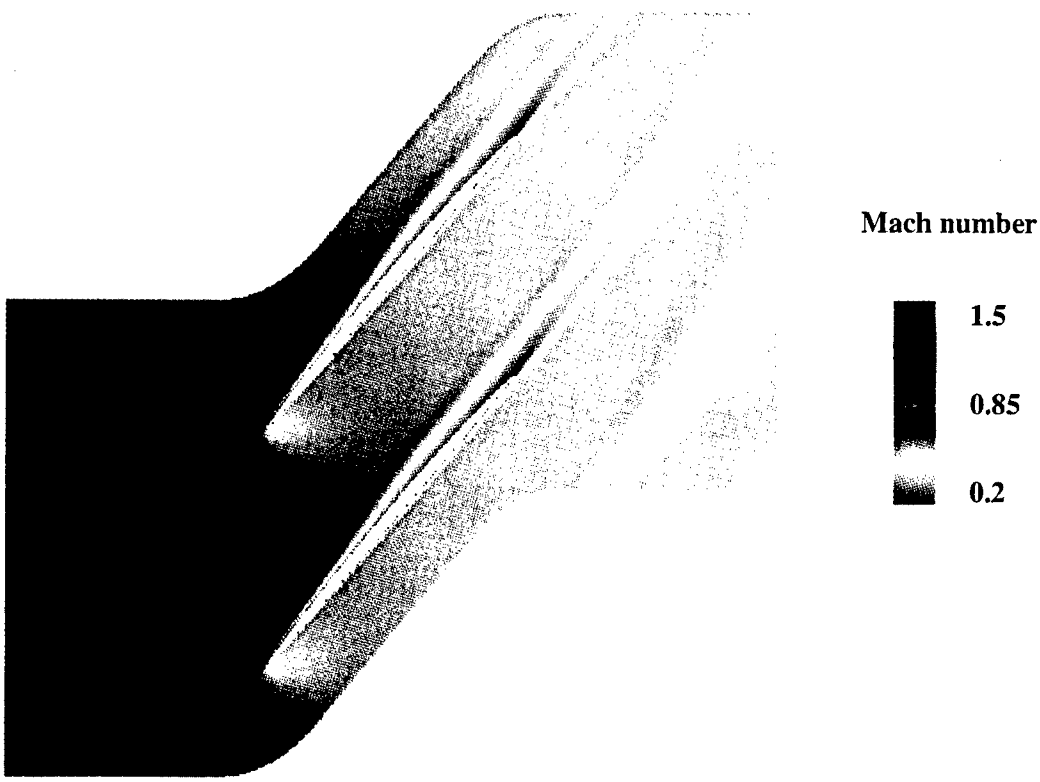


Fig. 18 Computed flow field from unsteady 2.5D k−ε code (subsonic cascade data at 6° positive incidence)

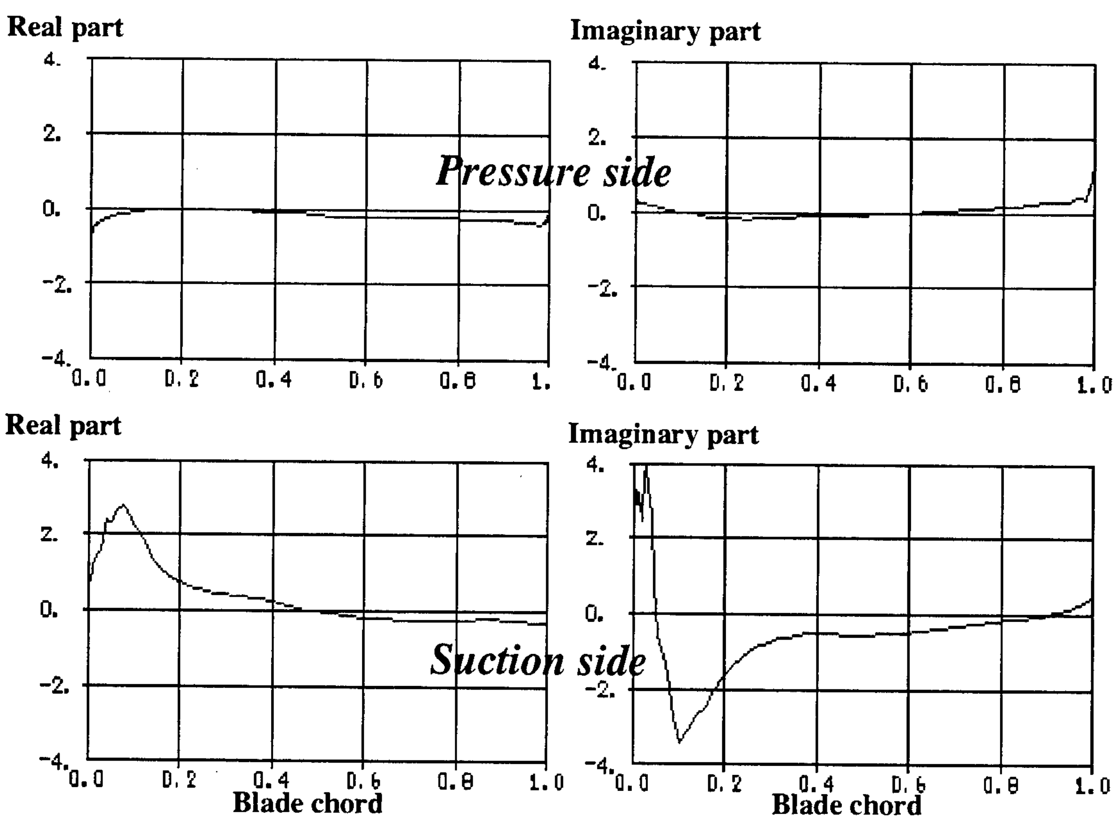


Fig. 19 Computed unsteady static pressures for torsion mode (subsonic cascade data at 6° positive incidence)

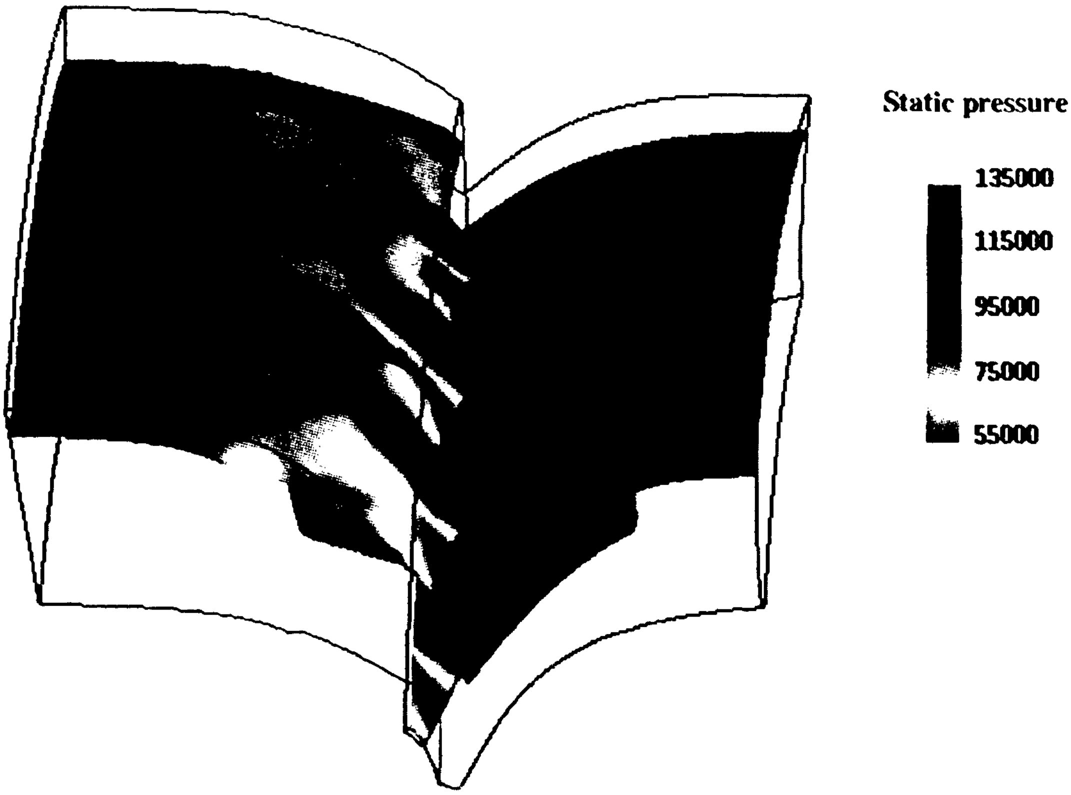


Fig. 20 Computed flow field from unsteady 3D EULER code (IGV/rotor1 unsteady interaction at part speed)

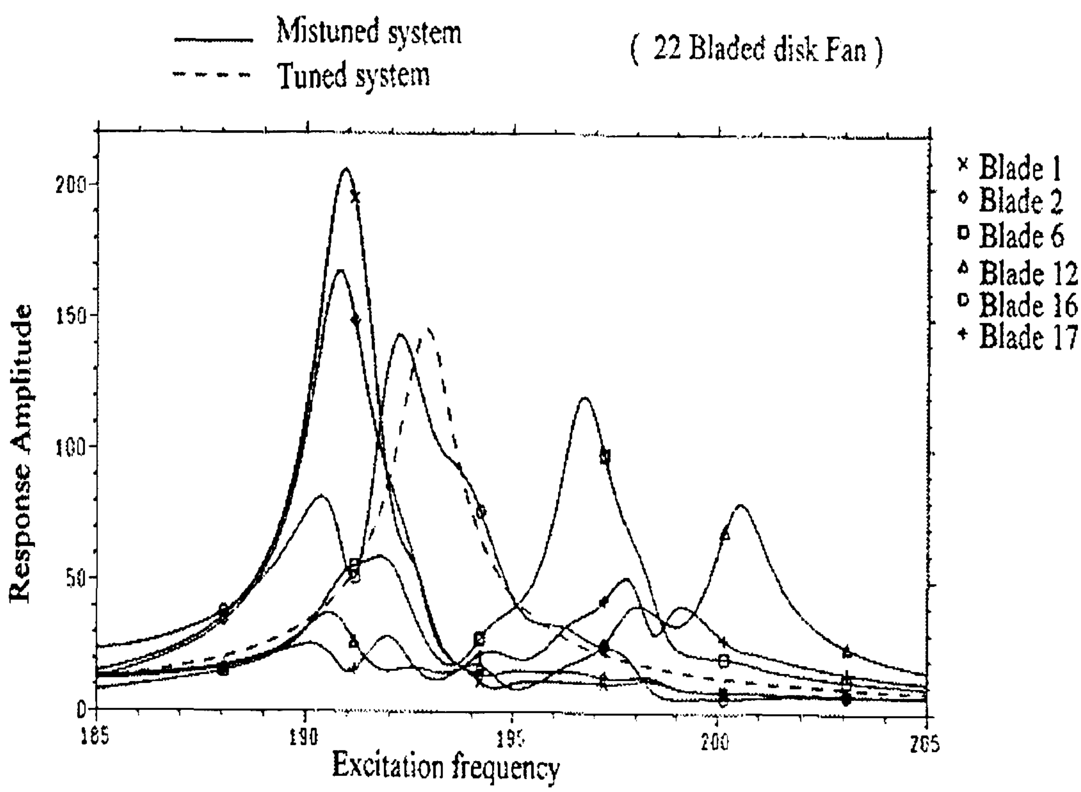
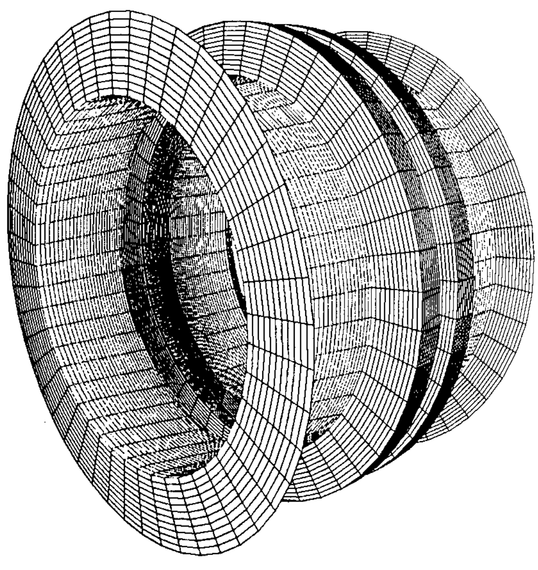


Fig. 21 Mistuning influence on forced response amplitudes

3D CODE



Coupling of : 3D unsteady Euler solution in blade-free volumes

with : multiple (tangentially uncoupled) unsteady through-flow solutions within blade-rows

Fig. 22 Description of 3D unsteady compressor model (3D Euler coupled with blade-row model)

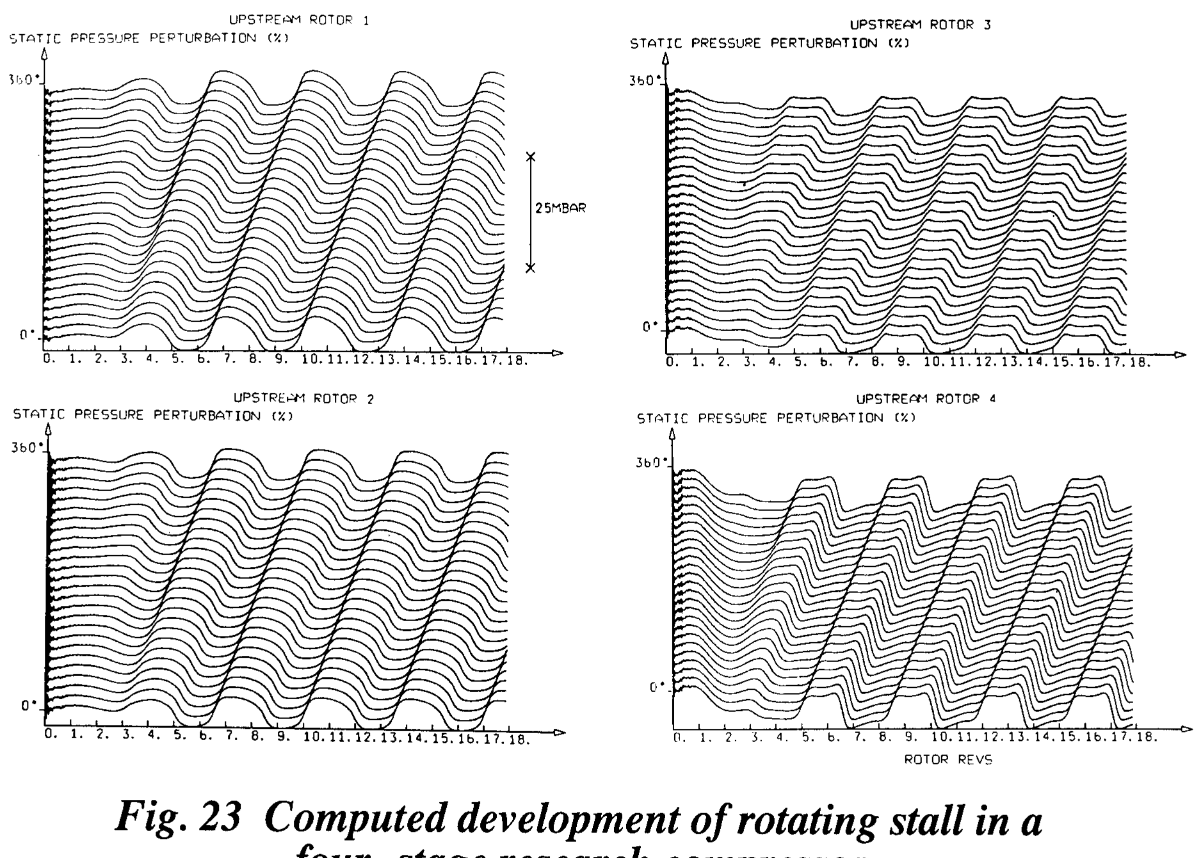


Fig. 23 Computed development of rotating stall in a four-stage research compressor

AGARD RTO Lecture Series No. 211

Integrated Multidisciplinary Design of High Performance Multistage Compressor Systems

First Order Manufacturing Constraints & Requirements

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MWB 1

The purpose of this section of the lecture series on Integrated Multidisciplinary Design of High Performance Multistage Compressor Systems is to discuss First Order Manufacturing Constraints not only in the context of Manufacturing, Process and Producability but their relevance to system considerations of performance, cost and operability. In every design there exists a performance ceiling and a cost floor between which multiple solutions exist. The purpose of a design is to create a product that will provide customer satisfaction in terms of expectations or technical requirements. In the military world this is the ability complete a specific mission and in the commercial world this is the ability to produce a revenue stream. The challenge is to translate these customer Critical To Quality (CTQ) requirements into hardware that will comprise a system. Consequently an understanding of the flowdown of the customer CTQ's to individual parts is essential if customer satisfaction is to be achieved. This represents the challenge in GEAE's Design For Six Sigma (DFSS) initiative and is driving the shift from deterministic to probabilistic design methodologies.

Paper presented at the RTO AVT Lecture Series on "Integrated Multidisciplinary Design of High Pressure Multistage Compression Systems", held in Lyon, France, 14-15 September 1998; Cologne, Germany, 17-18 September 1998; Cleveland, USA, 22-23 September 1998, and published in RTO EN-1.

First Order Manufacturing Constraints & Requirements

Interaction of Aerodynamic & Structural Analysis with Manufacturing

Session 1

- ☐ *Aerodynamic Design* — *Mr. Gregory T. Steinmetz*
  - *Effect of Tolerances*
- ☐ *Aeromechanical & Structural Design* — *Dr. Robert E. Kielb*, *Mr. Michael W. Bailey*
  - *Effect of Geometric Constraints*
  - *Effect of Tolerances*
  - *Effect of Material Selection*
  - *Configuration*

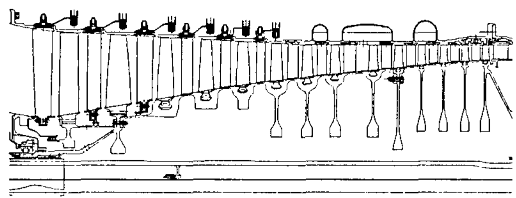
MWB 2

In this session of the lecture series we will discuss the effects of tolerances on aerodynamic design. Aerodynamic design translates the engine thermodynamic cycle into geometry that will be manufactured. It is responsible for achieving the key customer CTQ's of performance in the context of operability and efficiency.

The manufacturing process capability associated with this geometry establishes whether or not the intent is met. Ideally there should be feedback to the aerodynamic design to ensure we make what we design.

Compression System Airfoils

Tolerance Impact on Performance



- Compression system **must** deliver cycle specified flow and pressure ratio with acceptable stall margin and efficiency
- Compression component airfoils and flowpath must be manufactured as close to design intent as practically possible in order to maximize the probability of meeting cycle requirements

GTS 3

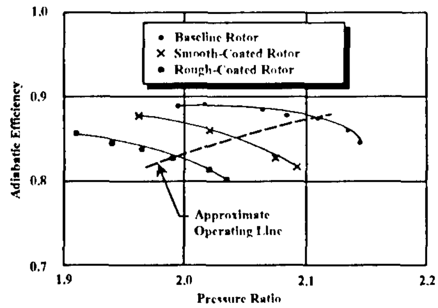
Compression system **must** deliver the cycle specified flow and pressure ratio with acceptable stall margin and efficiency.

Compression component airfoils and flowpath must be manufactured as close to design intent as practically possible in order to maximize the probability of meeting cycle requirements.

The following charts briefly discuss how some of the airfoil critical dimensions affect performance. This is not a complete airfoil tolerance list. Other dimensions such as lean, centrality and fillet radius can have a significant impact on performance. It should also be noted that the different key dimensions are reviewed separately but their total performance impact is dependent on coupled behavior.

Compression System Airfoils

Tolerance Impact on Performance



Efficiency-Pressure Ratio Characteristics at Design Speed

- **Surface Finish**
  - Impacts Efficiency & Pressure Ratio
  - Rough surfaces produce more skin friction drag (loss)
  - For constant pressure rise efficiency loss is 3.5-5.0 points
  - Along the Operating Line the Efficiency loss is 2.0 points

GTS 4

Airfoil surface finish impacts Compressor Efficiency and Pressure Ratio. The study by Suder et al. (Ref.1) investigated the performance deterioration of a high speed axial compressor rotor due to surface roughness and airfoil thickness variation. A coating approximately 10 times the roughness of the metal airfoil surface was applied to the rotor blade surface. For comparison, the tests were repeated with a smooth coating approximately the same roughness as the compressor blades. The effect the efficiency changes are shown by plotting the Adiabatic Efficiency against Pressure Ratio in the figure. For a constant pressure rise the loss is in the order of 3.5 to 5.0 points for the rough coating after adjusting for the effects of thickness. An approximate operating line is shown in the figure. The efficiency loss along the line is 2.0 points for the rough coating after adjusting for the coating thickness.

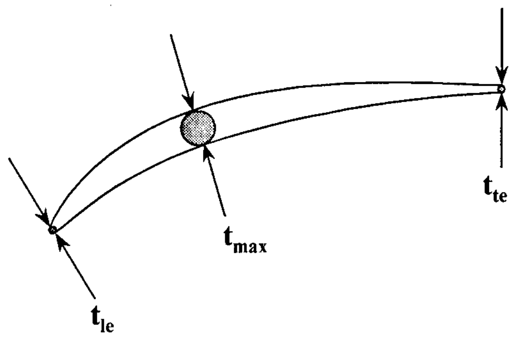
The efficiency loss for the stator would be considerably less because of the reduced velocities, possibly of the order of one third the loss of the rotor.

The surface finish resulting from the forging or pinch and roll operation should produce the desired surface finish. On milled bladed disks or blisks the surface finish is dependent on the geometry, material and size of the airfoils. For this reason Electro Chemical Machining (ECM) is the preferred method since it has an inherently better surface finish and does not impose tool loads and hence deflections on the airfoils.

Compression System Airfoils

Tolerance Impact on Performance

- **Thickness**
  - Critical to Flow and Efficiency for subsonic and transonic blades
  - Excessive thickness increases flow blockage (adds loss and reduces flow passing capability)
  - For constant pressure rise Efficiency loss is 2.5-3.5 points
  - Along the Operating Line the efficiency loss is 3.0 points



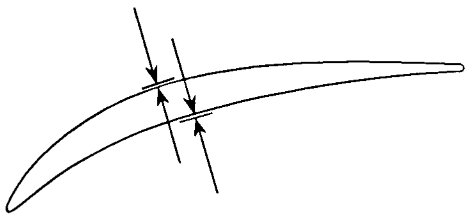
GTS 5

Airfoil thickness is critical for compressor flow and efficiency for subsonic and transonic blades. Excessive thickness increases flow blockage, adds loss and reduces flow passing capability. Airfoil thickness is controlled during the forging process on individual blades and during the machining operation on bladed disks or blisks. To achieve the correct thickness, a forged or pinch and rolled blade may subsequently be electro-chemically machined to compensate for die wear.

The coating that Suder et al. (Ref.1) applied to each surface of the blade was nominally 0.025 mm (0.001 in.) and no greater than 0.050 mm (0.002 in.) thick. A coating thickness of 0.025 mm (0.001 in.) on the blade pressure and suction surfaces corresponds to 10% of the leading edge thickness at the hub, 20% of the leading edge thickness at the tip and only 3% of the throat width at the blade tip. The amount of thickness added to the blade surfaces by the coatings was well within the overall blade thickness manufacturing tolerance of $\pm$ 0.125 mm (0.005 in.) and comparable to the leading edge blade thickness manufacturing tolerance of $\pm$ 0.050 mm (0.002 in.). For a constant pressure rise the efficiency loss is in the order of 2.5-3.5 points for the smooth coating. The efficiency loss along the operating line is 3.0 points for the smooth coating. Leading edge thickness is critical for Foreign Object Damage (FOD) resistance but thickening the leading edge to provide FOD resistance will increase flow blockage. The main driver in FOD is high compressor blade tip speed which is a characteristic of high performance compressors. Consequently building in FOD tolerance by thickening the blade leading edge will result in a performance degradation.

Compression System Airfoils

Tolerance Impact on Performance



- **Contour**
  - Leading edge shape is critical to all aspects of performance
  - Proper shape helps prevent leading edge flow separation
  - Transonic blade leading edge shape design intent must be met to minimize shock loss and meet unique incidence requirement
  - Overall airfoil contour critical to achieving design loading distribution

GTS 6

The leading edge shape is critical to all aspects of performance. Proper shape helps prevent leading edge flow separation. Transonic blade leading edge shape design intent must be met to minimize shock loss and meet unique incidence requirements. The overall airfoil contour is critical to achieving blade design loading distribution.

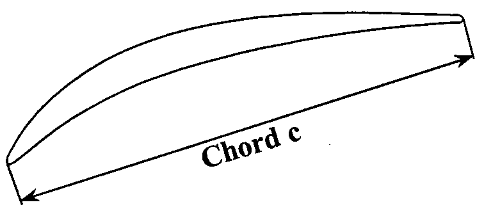
Suder et al. (Ref.1) presented performance measurements for a number of coating configurations at 60%, 80% and 100% design speed. The results indicate that the thickness roughness over the first 10% of the blade chord accounts for virtually all of the observed performance degradation for the smooth coating compared with about 70% of the observed performance degradation for the rough coating.

Measurements and Computational Fluid Dynamics (CFD) analysis were performed on the baseline blade and the full coverage smooth and rough coatings. The results indicate that coating the blade causes a thickening of the boundary layers. The interaction between the rotor passage shock and the thickened suction surface boundary layer then results in an increase in blockage which reduces the diffusion level in the rear half of the blade passage, thus reducing the aerodynamic performance of the rotor.

Ref.1 Suder K. L., Chima R.V., Strazisar A. J., and Roberts W. B. The effect of adding roughness and thickness to a transonic axial compressor rotor. NASA Technical Memorandum 106958

Compression System Airfoils

Tolerance Impact on Performance



- **Chord**
  - Impacts Flow, Efficiency and Stall Margin
  - Inadequate chord can result in higher surface loading (weaker boundary layers) which can cause underturning and/or flow separation

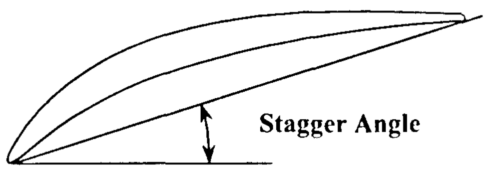
GTS 7

The airfoil chord impacts the flow efficiency and stall margin.

An inadequate chord can result in higher airfoil surface loading resulting from weaker boundary layers. This effect causes underturning and/or flow separation.

Compression System Airfoils

Tolerance Impact on Performance



- **Stagger**
  - Impacts Flow, Efficiency and Stall Margin
  - Incorrectly set leading/trailing edge angles may lead to premature flow separation and/or incorrect turning
  - In multistage machines, improperly staggered airfoils will cause stagewise loading redistribution
  - This may impact stall margin, efficiency and flow

GTS 8

Airfoil stagger angle impacts flow, efficiency and stall margin. Incorrectly set leading and trailing edge angles may lead to premature flow separation and/or incorrect turning. In addition stagger angle variation (and to a lesser extent thickness tolerance) can introduce compressor blade passing frequency excitations which should be accounted for in the aeromechanical design.

In a practical application this can manifest itself as springback during the manufacturing process or untwist due to centrifugal loading. A good example in concurrency is the integration of aerodynamic design, structural design and manufacturing to achieve the correct stagger angle for airfoils. There is generally significant iteration required to compensate for airfoil springback during the forging or pinch and roll process. Some materials, notably titanium alloys, have significantly different springback characteristics or "memory". In this respect bladed disks or blisks, where airfoils are machined from solid by milling or Electro Chemical Machining (ECM), it is easier to maintain stagger angle.

In multistage machines improperly staggered airfoils will cause stagewise loading redistribution. This may impact stall margin, efficiency and flow.

First Order Manufacturing Constraints & Requirements
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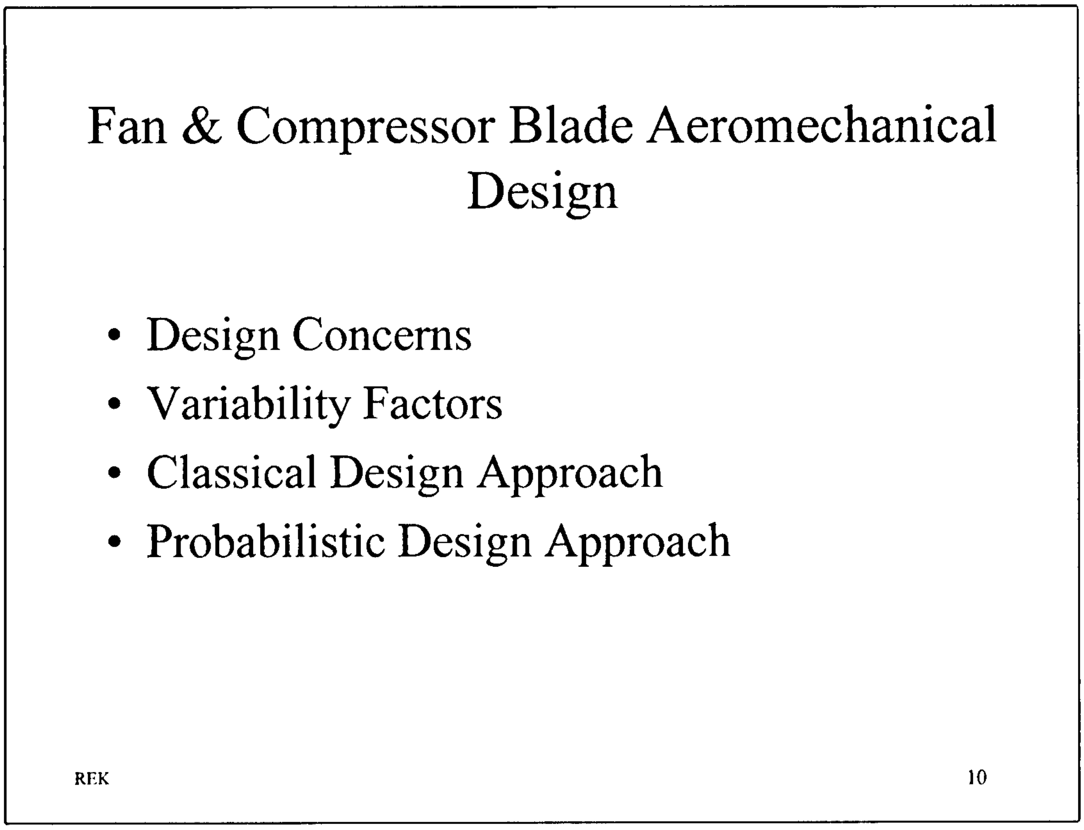
MWB 9

This portion of the lecture explains how manufacturing variations are considered in the aeromechanical design of fan and compressor airfoils and the structural design of rotating hardware. The effects of geometric variation created by the manufacturing process capability and robust design techniques used to minimize their impact will be discussed.



The background is set by defining the aeromechanical design concerns and then by listing a comprehensive set of variability factors which effect the aeromechanical response over the life of a compressor airfoil. It is shown how manufacturing variability is one of these factors. Next the classical design approach is shown with emphasis on how manufacturing variability is considered. Finally, the new probabilistic design approach is described.

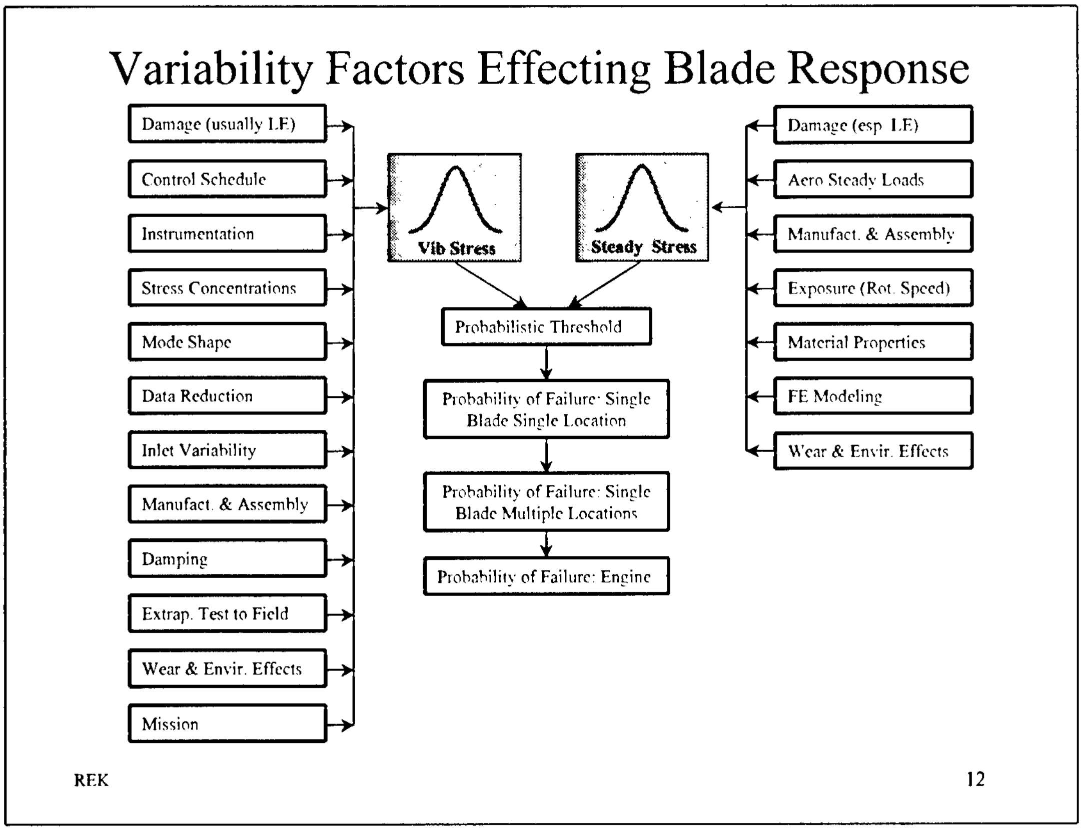
Aeromechanical Design Concerns

- Flutter Margin
- Frequency Placement & Resonant Response
- Stall Overstress Capability
- FOD/Ingestion/Erosion Capability
- Attachment Strength

REK 11

The two most important aeromechanical design concerns are flutter and resonant response. Flutter is a self excited vibration in which the airfoil extracts energy from the airflow. A common type of blade resonant response is when blades pass through the wakes of upstream vanes. The resonance occurs when the forcing frequency is equal to the blade's natural frequency. Although manufacturing variability can effect both flutter and forced response, the latter effect is the most compelling. This is because variability typically has a beneficial effect on flutter and a detrimental effect on forced response.

Three additional aeromechanical design concerns are stall overstress capability, leading edge damage capability and attachment strength. Of these attachment strength is most sensitive to manufacturing variability.



Durability of fan and compressor airfoils is generally assessed by specifying the steady and vibratory stress at every point in the structure. A Goodman approach is then used to relate these stresses to the capability of the material including the effects of damage. This chart shows how variability effects the overall durability of an airfoil. Two important, and all encompassing, categories of blade response variability are manufacturing and assembly variation and wear and environmental variation. Examples of manufacturing effects are geometric variation in vanes, fit-up variation between struts and flaps, mis-rigged variable geometry and inlet variation. Examples of wear effects are dovetail wear, shroud wear and tip rub. This lecture limits its attention to the area of manufacturing variability.

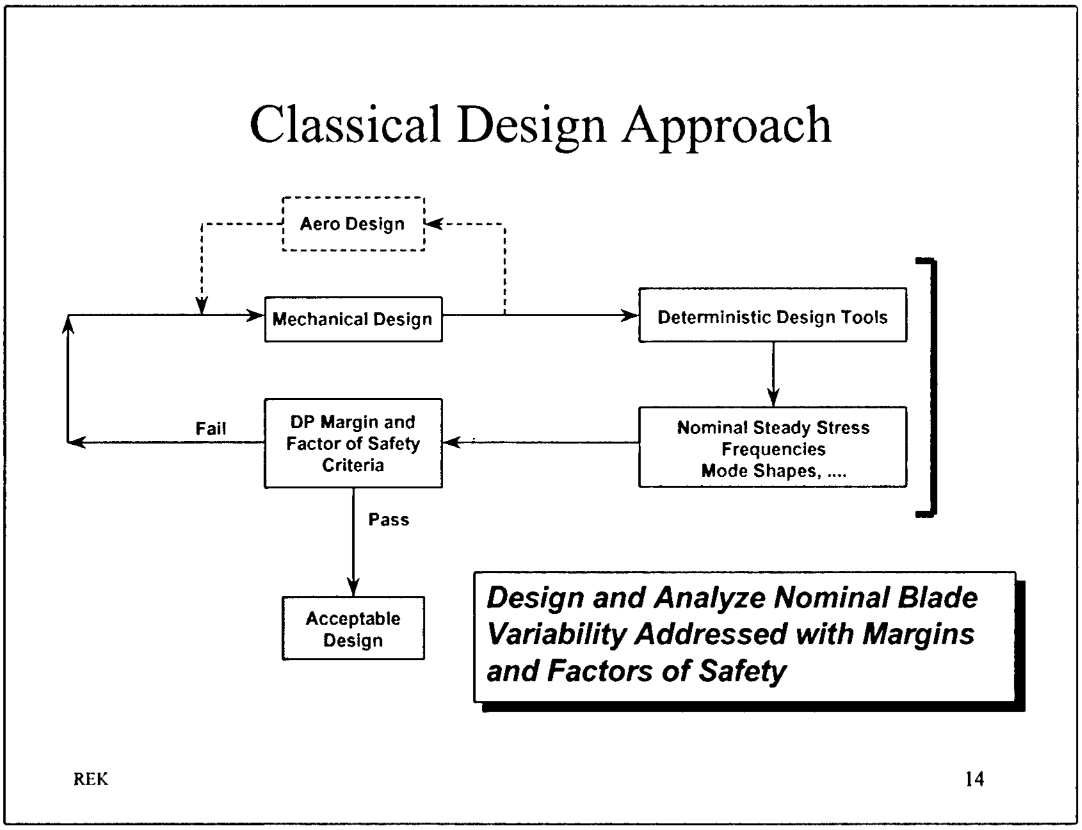
Classical Design Criteria

- Steady Stress
- Leading Edge Ruggedness
- Frequency Margin to Known Excitations
- Frequency Separation Criteria
- Reduced Velocities
- Mode Shape Parameters
- Hot Spot for Panel Vibratory Modes

REK 13

This chart shows the most important aeromechanical analysis parameters. The four parameters of most interest are steady stress, modal frequencies, mode shapes and modal strain distributions. Manufacturing variations effect all of these quantities.

The steady stress is limited to provide for some vibratory capability. This is especially true for the blade leading edge. Modal frequencies are predominately used to set adequate margin to known excitation sources. The required margins are based on experience on the effect of manufacturing variability on frequency. The modal frequencies are also used to ensure that modes have adequate frequency separation. When modes are too close together a high level of variability can be seen in blade response. Reduced velocities are flutter parameters which are also effected by frequency variation. Flutter is also effected by the mode shape. Hot spots are areas of locally high vibratory strain and they can be significantly effected by manufacturing variation. The hot spot parameter is defined as the maximum local strain normalized by the local strain energy.



The classical aeromechanical design approach for blades uses deterministic design analysis to analyze the nominal blade geometry. Manufacturing variability is taken into account by requiring margins, or applying Factors of Safety, when compared to design criteria. Distributions of design analysis parameters, such as blade frequency, are not estimated. The margins and Factors of Safety are "calibrated" by experience from previous successful and unsuccessful designs. Of course, this approach has been used in engineering design since the early days of design analysis. The downside of this approach is that it is typically overly conservative and can reject good designs. Alternatively, this approach can be unconservative and allow bad designs to make their way to production.

Manufacturing Variability

Key Airfoil Characteristics for Cantilevered Titanium Airfoils

- Maximum Thickness/Chord vs Span
- Chord vs Span
- Leading Edge Thickness vs Span
- Trailing Edge Thickness vs Span
- Maximum Thickness vs Chord vs Span
- Airfoil Fillets
- Stagger Angle vs Span
- Tilt & Lean
- Material Properties

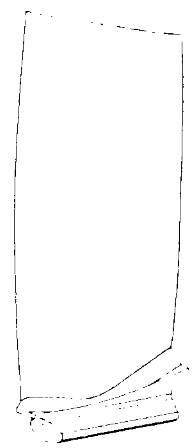
REK 15

This chart shows a minimal set of blade geometry parameters which are key to determining the success of a design. As such the effect of manufacturing variation on these parameters is important and must be controlled.

The maximum thickness/chord and chord are extensively used to set steady stress and frequency margins. The edge thicknesses determine the ability to withstand damage. The location of the maximum thickness as a function of chord plays a significant role in controlling the hot spots. An adequate airfoil/platform fillet is necessary to control stress concentrations. Stagger angle is a controlling parameter for flutter. Tilt and lean are used to control the root steady stress of the airfoil. Material selection is based on low cycle and high cycle fatigue strength, modulus/density ratio, temperature capability, damage sensitivity, wear/fretting sensitivity, and cost.

Probabilistic Design Approach

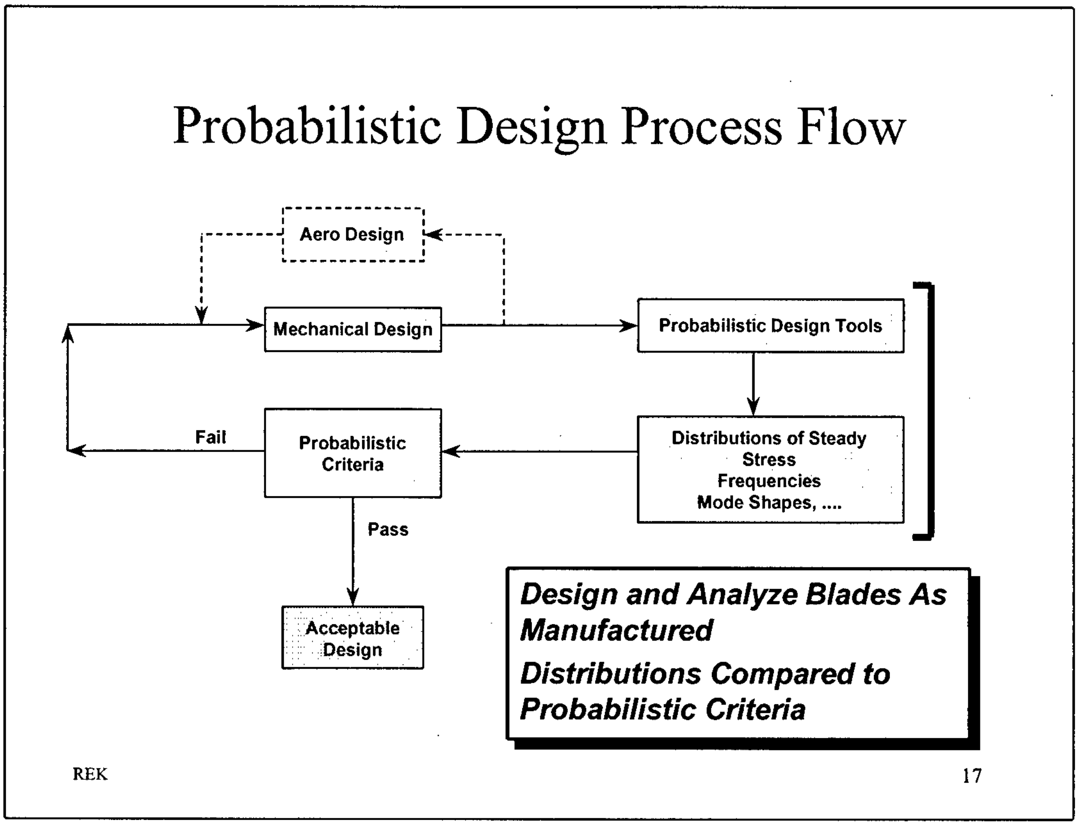
- Philosophy
- Example



REK 16

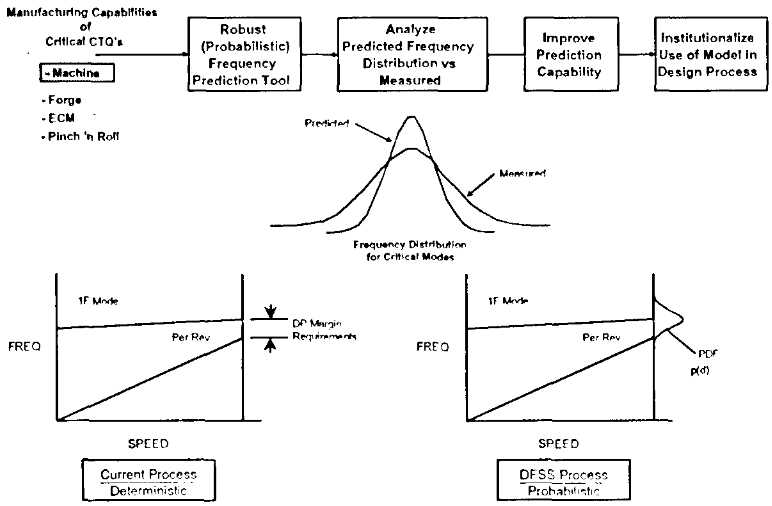
As previously stated the classical approach in blade aeromechanical design is to use margins and Factors of Safety to take manufacturing variation into account. However, we are now starting to design blades by quantitatively considering manufacturing variability. This approach is now addressed. First, the philosophy will be described and then a example will be shown.

Factors of Safety are generally based on past experience and consequently are parametric and may not necessarily be physics based. For example a 10% margin may be insufficient, adequate or overkill. Unfortunately only when it is insufficient does it get peoples attention.



In the probabilistic design process the design analysis considers the distribution of blades that will be produced from a given design by a given process. These distributions will be evaluated against probabilistic criteria. The evaluation will generally be a probability that criteria will be violated. The process is expected to minimize the chances for under- or over-conservative design. The result is a high quality, robust product. The following charts show an example of the process for blade frequencies.

Example of Frequency Prediction Process



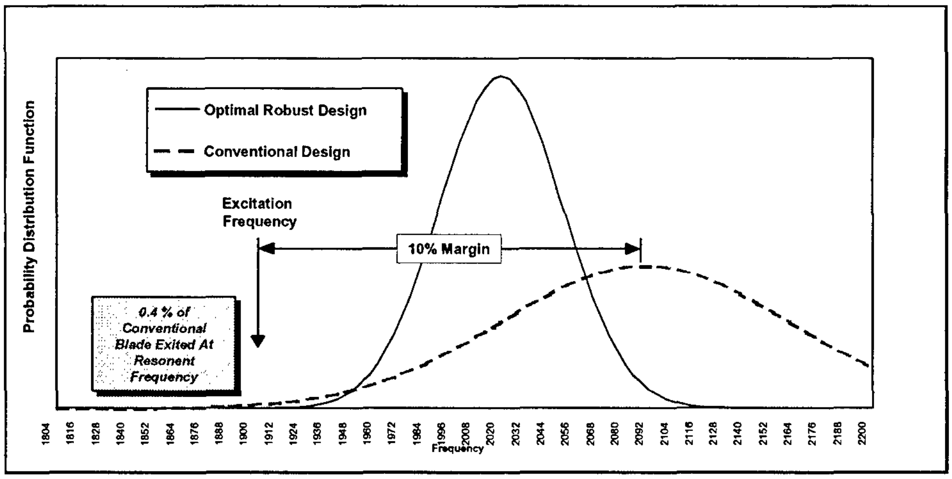
REK 18

This chart shows how the process will be institutionalized for the frequency placement of a machined blade. The probabilistic frequency prediction tool relies heavily on finite element analysis. These predictions will be compared with measured frequencies to define the key variables effecting frequencies and for calibration purposes.

In application this probabilistic design tool will be used to predict the distribution of frequencies for comparison with the known excitation sources. The probability that a blade will have a natural frequency which approaches the excitation frequency will then be calculated to determine the adequacy of the design.

Here the margin is based on process capability and design intent, not past experience. Thus the potential exists to open up tolerances to create a more producible design that meets design intent.

Example of Frequency Margin

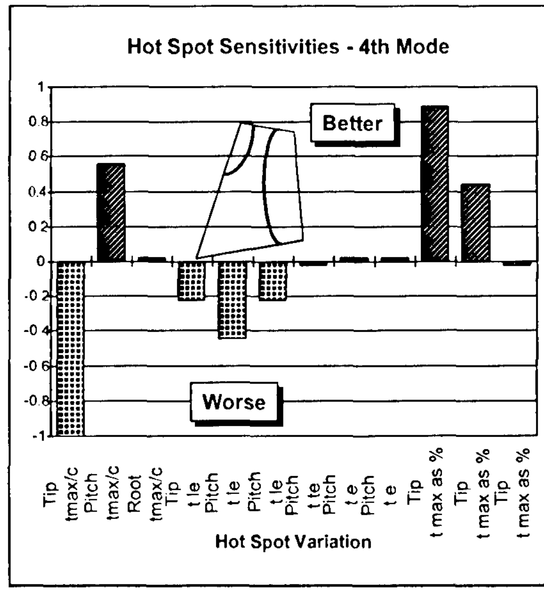


REK 19

As an example this chart shows a conventionally designed blade in which the mean frequency was required to have 10% margin to the excitation frequency. The example shown is an unconservative design in that 0.4% of the blade will have frequencies at or below the excitation frequency. On the contrary the probabilistically designed blade has caused a much tighter frequency spread. Although the mean frequency is less than conventionally designed blade, this optimal design has virtually no blades, with frequencies at or below the excitation frequency.

Fan Rotor Stage1 Sensitivity Study

- First Step - Prediction Of Sensitivities (Key Control Characteristics - KCC's)
- Current Production Fan Blade used as example
- Predicted Sensitivities compare well with those found by 20 manual calculations
- Sensitivities based on $+1\sigma$ change
- Hot Spot Parameter is the Maximum Local Strain normalized by the Total Strain Energy



REK

20

Local strains based on nominal dimensions vary from compressor blade to compressor blade. This is further complicated by the addition of tolerance effects. This study was performed to determine which parameters drive these strain distributions or hot spots. First Step is the prediction of sensitivities or Key Control Characteristics (KCC's).

A Current Production Fan Blade is used as an example.

Hot spot sensitivities are based on tmax/c, t leading edge, t trailing edge and tmax as a % of chord for Tip, Root and Pitch. It can be seen that tmax/c has a significant worsening effect at the tip, creates an improvement at the pitch but has negligible effect at the root. Leading edge thickness has a worsening effect for tip, root and pitch, whereas trailing edge thickness has a negligible effect. In addition tmax as a percentage of chord has an improving effect if the location of the maximum airfoil thickness is moved forward.

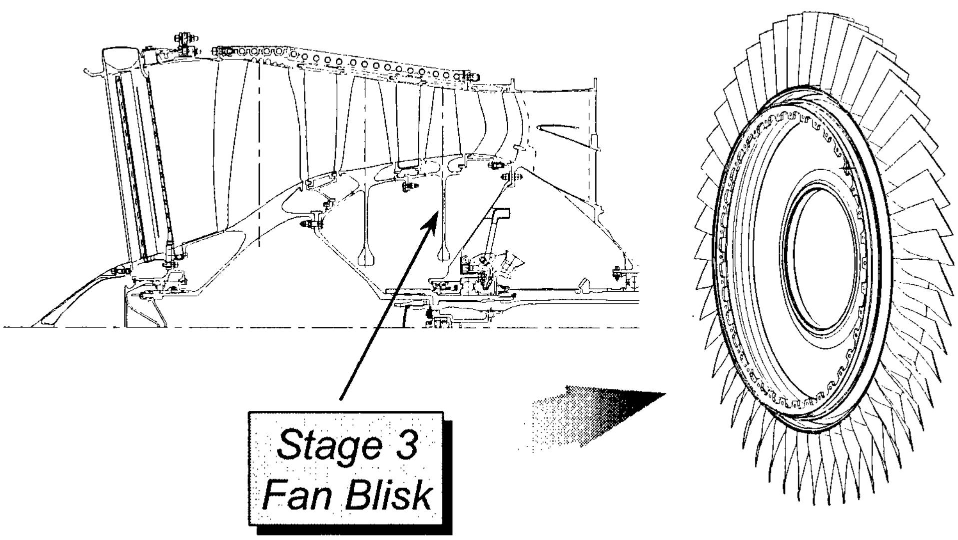
Historically the airfoil maximum thickness tmax was located at approximately 50% chord. In an effort to achieve better performance this was moved to 60% chord. It was subsequently found that this increased the hot spot sensitivity.

Predicted sensitivities compare well with those found manually in 20 calculations.

Sensitivities based on +1 sigma change.

Hot Spot Parameter is the maximum local strain normalized by the total strain energy.

Stage 3 Fan Blisk Design Study

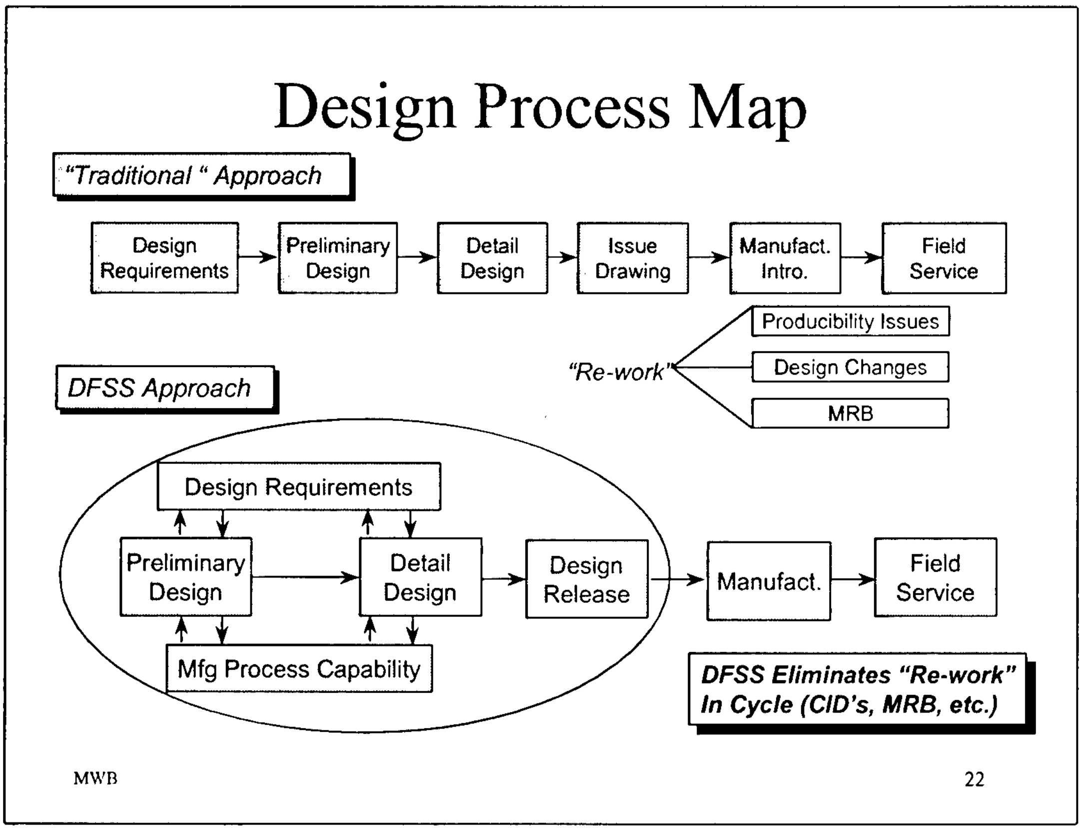


MWB 21

We have just discussed the structural effects of manufacturing tolerances on blade airfoils. We will now consider the structural effects on the disk that supports the airfoils.

The purpose of the compressor rotor structure is to support the rotating airfoils. Thus the centrifugal and gas loads are transmitted through the blade platform, shank and dovetail into the disk. The trade between the number of stages, disk life and cost may drive the design to a blisk configuration.

Although the example we will discuss is a disk with integral blades or blisk, this discussion would apply to conventional disks.



Shown above are process diagrams for the "Traditional" Design approach and the DFSS approach. The "Traditional" approach is serial in nature and usually results in some kind of rework or redesign resulting from producibility issues, design changes or part deviations from the drawing (MRB). In the DFSS or Robust Design approach, the key dependencies are analyzed and a robust design is produced before design release thus minimizing manufacturing and field problems.

QFD Results - Stage 3 Blisk

QFD Relationships
Strong = 9
Moderate = 3
Weak = 1

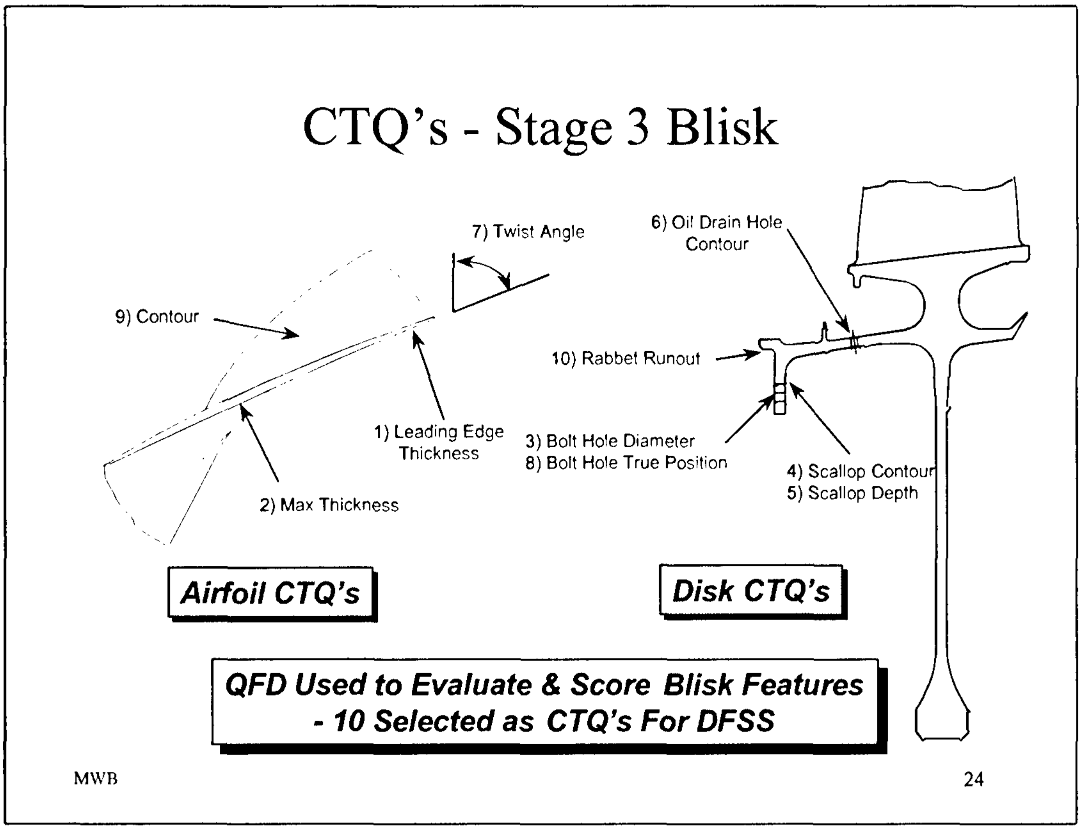
Part Features (HOW's) Reference #		22	26	2	5	6	7	27	3	28	13	19	20	29	30	1	9	14
Customer Expectations (WHAT's)	CUSTOMER IMPORTANCE	Leading Edge Thickness	Maximum Thickness	Forward Flange Bolt Hole Diameter	Forward Flange Scallop Contour	Forward Flange Scallop Depth	Oil Drain Hole Contour	Twist Angle	Forward Flange Bolt Hole True Position	Contour	Forward Flange Rabbet Runout & Concentricity	Forward Seal Diameter & Runout	Aft Seal Diameter & Runout	Height	Chord	Airfoil Root Fillet	Bore Diameter	Forward Flange Flatness / Parallelism
LIFE / SAFETY / RELIABILITY	5	9	3	9	9	9	9	3	9	1		1	1	1	3	3	3	1
PERFORMANCE	4	9	9					9		9		3	3	3	3	1	1	
ASSEMBLY & VIBRATION	3	1	9					1	1	1	9	3	3	3	1	1	1	3
MAINTAINABILITY / REPAIRABILITY	4	9	3	3	3	3	3				3	3	3	3	1	1	1	3
PERCEIVED QUALITY	2	1	1	1					1		1	1	1			1	1	1
Part Features (HOW's) Reference #		22	26	2	5	6	7	27	3	28	13	19	20	29	30	1	9	14
CUSTOMER TOTAL SCORE		122	92	59	57	57	57	54	50	44	41	40	40	38	34	28	28	26
CUSTOMER SCORE RANKING		1	2	3	4	4	4	7	8	9	10	11	11	13	14	15	15	15
CTQ For DFSS		X	X	X	X	X	X	X	X	X	X							

Part Features (HOW's) Reference #	21	4	8	25	10	36	37	35	12	34	40	15	38	17	18	32	33	11
Customer Expectations (WHAT's)	Flange Thickness	Forward Flange Bolt Hole Break Edges	Oil Drain Hole Position / Alignment	Trailing Edge Thickness	Bore Width	Leading Edge Flowpath Drop	Trailing Edge Flowpath Drop	Flowpath Contour	Forward Flange Rabbet Diameter	Visual	Shot Peening	Thickness Variation	Leading Edge Flowpath Radius	Damper Nub Thickness	Damper Nub Diameter	Axial Lean	Centrality	Web Thickness
LIFE / SAFETY / RELIABILITY	3	3	3	1	3			1			3	1		1	1	1	1	1
PERFORMANCE				3	1	3	3	3					3			1	1	
ASSEMBLY & VIBRATION	3			1		3	3	1	3	1		3		1	1	1	1	
MAINTAINABILITY / REPAIRABILITY	1	3	3	1	1	1	1	1	3					1	1			1
PERCEIVED QUALITY				1	1				1	9	1		1					
Part Features (HOW's) Reference #	21	4	8	25	10	36	37	35	12	34	40	15	38	17	18	32	33	11
CUSTOMER TOTAL SCORE	28	27	27	26	25	25	25	24	23	21	17	14	14	12	12	12	12	9
CUSTOMER SCORE RANKING	15	19	19	21	22	22	22	25	26	27	28	29	29	31	31	31	31	35
CTQ For DFSS																		

Blisk Characteristics Evaluated and Scored
10 Selected as CTQ's For DFSS

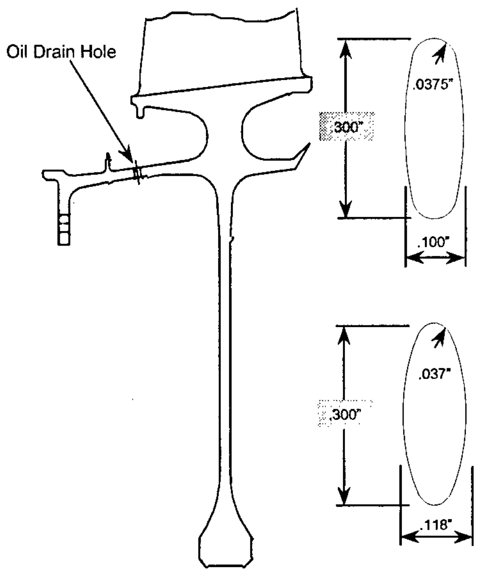
MWB 23

Quality Functional Deployment (QFD) was used to rank CTQ flowdown based on customer expectations or WHAT's based on Life/Safety/Reliability, Performance, Assembly & Vibration, Maintainability/Repairability and Perceived Quality. The QFD relationships to part features or HOW's were ranked as Weak, Moderate and Strong with scores of 1, 3 and 9 respectively. As a result of this QFD, 10 blisk characteristics were selected for DFSS. These were 1) Leading Edge Thickness, 2) Maximum Thickness, 3) Forward Flange Bolt Hole Diameter, 4) Forward Flange Scallop Contour, 5) Forward Flange Scallop Depth, 6) Oil Drain Hole Contour, 7) Twist Angle, 8) Forward Flange Bolt Hole True Position, 9) Contour, and 10) Forward Flange Runout & Concentricity.



The 10 CTQ's selected for DFSS were ranked in order of importance and include both airfoil and disk CTQ's. The airfoil CTQ's are the same as for compressor blades (1,2,7 & 9) but are machined from solid, so they are well within the process capability of the Electro Chemical Machining Process. These associated with the disk either affect assembly functionality (3,8 & 6) or disk structural integrity (4,5 & 6). On a bladed disk design, the blade to disk attachment would constitute a life limiting area.

Robust Oil Drain Hole



Baseline Hole Design
- Based on a current engine fan oil drain hole.
- Peak stress is at the end tangency point.
- Very sensitive to manufacturing process variation.
- Drawing places tolerance on length and width rather than contour - may not adequately control shape.

New Robust Hole Design
- Hole widened to move peak stress to side of hole and shield tangency point.
- Similar to other product line re-design philosophy.
- Reduced sensitivity to process variation.
- Drawing delineation templates redefined to better match manufacturing process.
- Design achieves ~6σ.

MWB 25

Baseline Hole Design

Based on a current production engine fan oil drain hole

Peak stress is at the end tangency point

Very sensitive to manufacturing process variation

Drawing places tolerance on length and width rather than contour and may not adequately control the shape

Robust Hole Design

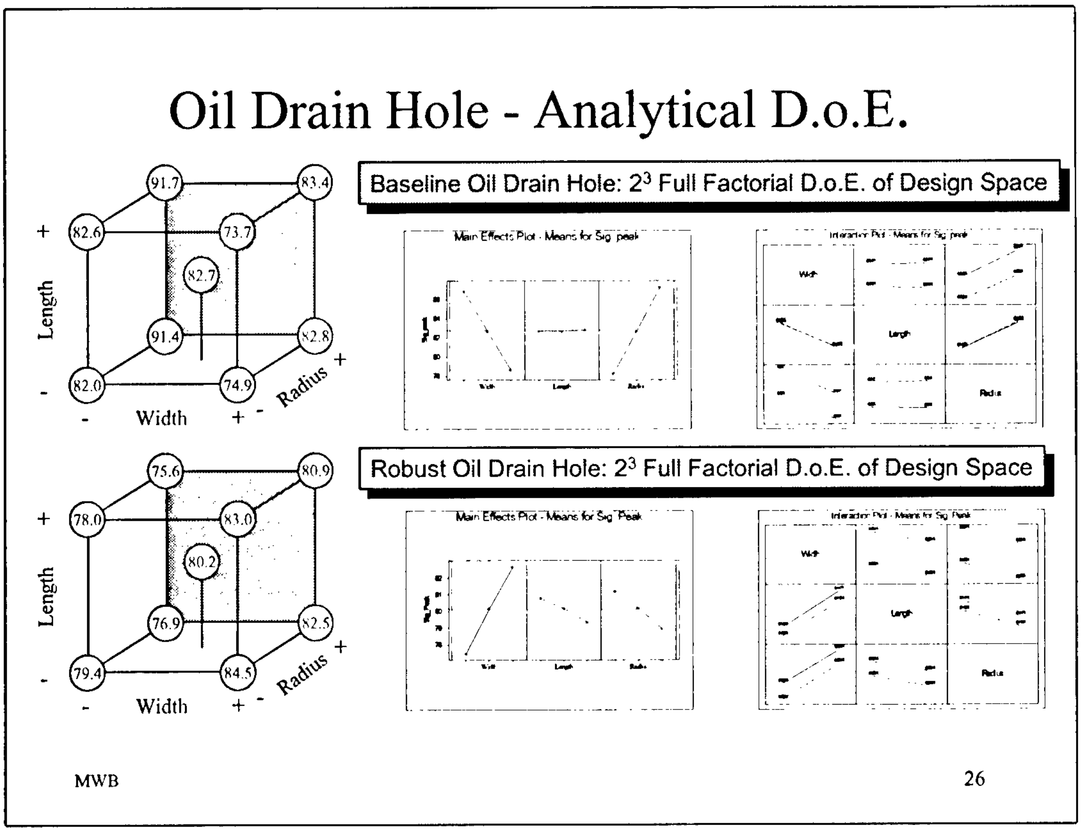
Hole widened to move peak stress to side of hole to shield tangency point

Similar to other product line re-design philosophy

Reduced sensitivity to process variation

Drawing delineation template revised to better match the manufacturing process

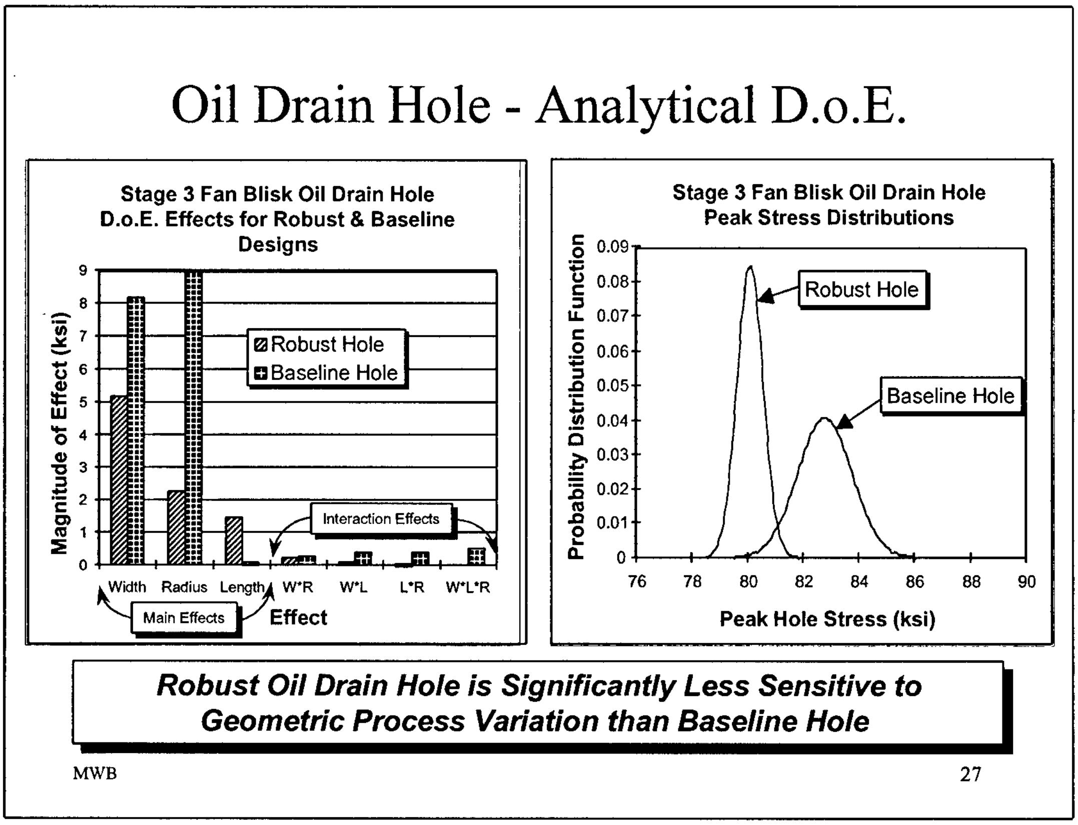
Design achieves approximately Six Sigma



A 2^3 Full Factorial Design of Experiments was performed for both the Baseline Hole and the Robust Hole.

A cube helps us visualize the experimental space covered by the 3 factors. Each corner represents 1 set of experimental conditions. Hence 2^3 represents (Two Levels)$^{\text{(Three Factors)}}$ which equals 8 experimental conditions. The main effects are Width, Radius and Length. Interaction effects are Width*Radius, Width*Length, Length*Radius and Width*Length*Radius. A center point is added by extrapolation to provide additional data.

The Main effects plots for Width, Length and Radius for both the Baseline and Robust Oil drain holes are shown in the center of the slide. The greater the slope the more dominant the effect. On the Baseline oil drain hole the Width and Radius have a significant effect but the Length has no effect. On the Robust oil drain hole the Width has the dominant effect but the Length and Radius have less but similar effects. It is worth noting that the slopes on the Width for the Baseline and Robust oil drain holes are reversed. The Interaction plots are shown on the right of the slide. Here the slopes being parallel indicates that there are no interaction effects between Width*Radius, Width* Length, Length*Radius and Width*Length*Radius.



1000 run Monte Carlo simulations were performed to establish the probability distribution for both the baseline and robust holes. It can be seen from the Pareto chart on the left that the dominant variables are Width and Radius with Length being a secondary effect. The interaction effects of Width*Radius, Width*Length, Length*Radius and Width*Length*Radius have minimal effect. The robust hole design has a 40% reduction in stress resulting from the effect of Length and a 75% reduction in stress resulting from the effect of Radius.

From the peak stress distribution plots on the right it will be noted that the robust hole design has a lower mean stress and narrower stress range which results in a higher Probability Distribution Function.

Summary

- *Aerodynamic Design translates the engine thermodynamic cycle into geometry that will be manufactured*
- *Aerodynamic Design is responsible for achieving the key customer CTQ's of Operability and Efficiency*
- *The effects of geometric variation caused by tolerances and their impact on Aerodynamic, Aeromechanical and Structural design have been discussed*
- *Probabilistic design techniques are replacing deterministic design techniques to create a more robust design by minimizing the effects of geometric variation*
- *Probabilistic design techniques are replacing Factors of Safety*
- *CTQ flowdown is an integral part of the robust design process*
- *Ideally there should be feedback to ensure design intent is met*

MWB 28

Summary

- Aerodynamic Design translates the engine thermodynamic cycle into geometry that will be manufactured.
- Aerodynamic Design is responsible for achieving the key customer CTQ's of operability and Efficiency.
- The effects of geometric variation caused by tolerances and their impact on Aerodynamic, Aeromechanical and Structural Design have been discussed.
- Probabilistic design techniques are replacing deterministic design techniques to create a more robust design by minimizing the effects of geometric variation.
- Probabilistic design techniques are replacing Factors of Safety.
- CTQ flowdown is an integral part of the robust design process.
- Ideally there should be feedback to ensure design intent is met.
- A useful example here is the Roman Architects. They had poor process capability in that they could not predict stress and hence the effects of loads. If the building collapsed they thickened everything up! Hence they built in huge Factors of Safety so much of what they built remains 2000 years later.

Compressor Matching and Designing for Tip Clearance

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1. SUMMARY
Compressors are designed for a specific duty reflected in the thermodynamic performance target, for design goals and for overall items in the specification, e.g. geometric dimensions, weight and cost. Early in the design phase general decisions need to be taken which, based on the technology level of the designing company, decide on the degree of challenge and thus the risk of the whole project.

For best performance the most important early decision is the level of stage loading and its distribution throughout the compressor. Together with the definition of the available cross section in each axial position, this determines the stagewise matching.

This lecture firstly describes the general rules of matching multistage compressors and secondly, from a design point of view, discusses one of the most important parameters influencing the matching during steady operation but even more significantly during transient operation, the design of tip clearance.

2. LIST OF SYMBOLS

F	force
T	temperature
DP	design point
SM	surge margin
WP	working point
a	specific mechanical work
c	fluid velocity
f( )	function of
h	enthalpy
j	dissipation
m	mass
$\dot{m}$	massflow
n	rotor speed (rpm)
n	polytropic coefficient
p	pressure
r	radius
u	circumferential velocity
α	flow angle in stationary frame of reference
β	flow angle in rotating frame of reference
φ	flow coefficient c/u
ψ	loading $2\ \Delta h / u^2$
π	pressure rise p_2/p_1
ω	angular velocity

Indices

CF	centrifugal
ISA	international standard atmosphere
ht	total enthalpy rise
m	meridional
red	reduced
yt	isentropic total enthalpy rise
1	inlet plane
2	outlet plane
I, II, III	stage numbering

3. INTRODUCTION
Multistage high-performance compressors are products of a highly specified industry, which has achieved excellent technology levels. The polytropic efficiency of modern machines even with more than ten stages is above 91%. Further improvements require significant technological efforts in areas, where the current understanding and prediction capabilities are not satisfactory. Tackling secondary flow as well as unsteady aerodynamic effects requires further advanced design tools and the acquisition of technology for advanced 3D-blading, e.g. with end bends.

The higher the performance target, the more difficult is the design necessitating closer cooperation of all disciplines. Examples of classical multidisciplinary design tasks are

- casing design,
- blading design,
- rotordynamic behaviour.

In compressor casings special arrangements have to be accommodated for the bleed off-takes, ensuring circumferentially equally distributed massflow and

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providing sufficient flow area in the manifolds and ducts. Their aerodynamic performance needs to be analysed to learn about the flow velocities, to derive flow capacity and to judge losses. The bleed flows have a significant effect on the thermal behaviour of the casing, influencing the tip clearance and thus the stability and performance of the overall compressor. To achieve the optimum solution in the minimum time with the least cost, close cooperation in the sense of simultaneous engineering is required /1/.

The multidisciplinary blading process is shown in fig. 3.1 and has been used as an example in an earlier lecture /2/. In summary, its challenge originates from the demand of high loading, high performance, mechanical requirements regarding life and vibrational behaviour, in combination with the general design and manufacturing optimisation. In comparison to conventional blading, special aerodynamic design features as end bends introduce significant additional mechanical risks and increase the complexity of the overall design task.

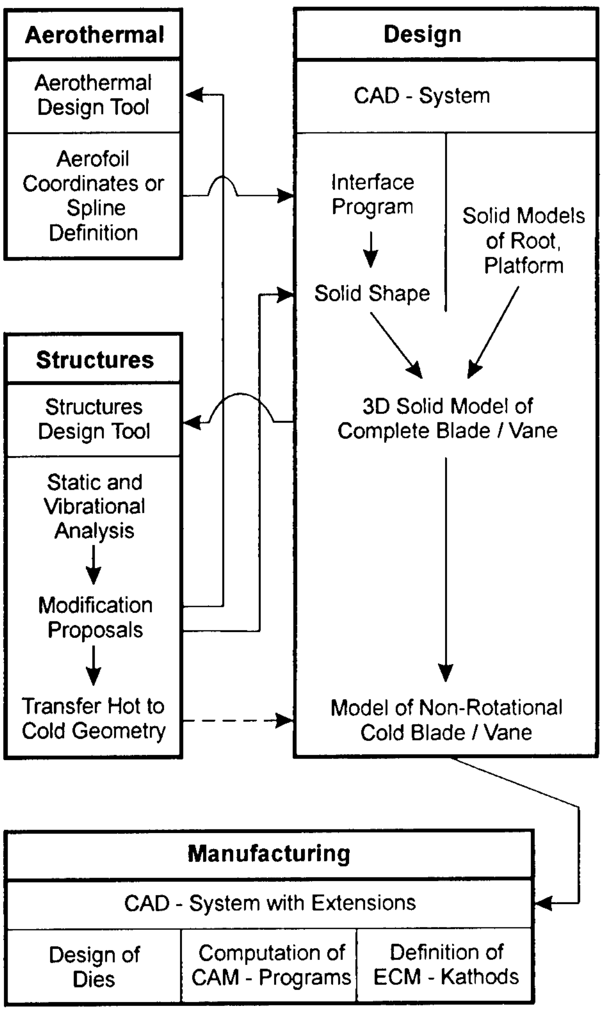

Fig. 3.1: Multidisciplinary Blading Process

The rotordynamic behaviour is analysed by just one discipline but it effects several aspects and changes require multidisciplinary solutions. One example is the influence of rotordynamic deflections on the tip clearance of the compressor. These deflections can either cause rubs which permanently increase the level of tip gap or cause a rotating nonuniform distribution of the gaps reducing the operational stability.

This lecture concentrates on two major aspects which need careful consideration in the design phase and which influence the stability of the compressor. Firstly, an introduction to the principles of aerodynamic stagewise matching is presented demonstrating the significance of this subject for the overall steady and transient performance. One dominating factor influencing the stagewise matching in steady and transient operation is the tip clearance between blade tips and casing and vane tips and hub respectively. Its design requires continuous attention to ensure that transient effects are minimised. Therefore the second part presents an attempt of identification of the influencing design parameters and their effects on the achievable level of tip clearance.

4. GENERAL STAGEWISE MATCHING CONSIDERATIONS

Compressors are utilised to pass a certain massflow with a simultaneous pressure increase of a certain ratio at high efficiency levels. This overall thermodynamic duty is reflected in its performance characteristic, fig. 4.1 /3/. In most applications the compressor is not run in a singular operating condition, but over a wide range. Depending on the duty, it is an operation at constant speed against a varying downstream throttle, fig. 4.1 line a, or an operation along a working line crossing different speeds with constant downstream throttle, fig. 4.1 line b, or a combination of both. For safe operation these working lines need to have a remaining positive distance from the stability limit or the surge line of the compressor. This margin is called the surge margin which can be defined in different ways; most common is the relation of the remaining pressure ratio between surge and working line, taken at a constant reduced aerodynamic speed, to the operating pressure ratio at this speed, fig. 4.2.

For compressors working under significant transient conditions, e.g. in jet engines with a changing environment, slow and fast transients, bleed and power extractions, g-loads and emergency operations, the critical operating conditions and manoeuvres have to be identified and surge margin monitors should be introduced. They basically show how the surge margin available under steady and thermally balanced conditions is eaten up during transients by secondary effects. Besides the working line excursion, changes in the surge line by tip clearance effects and influences of

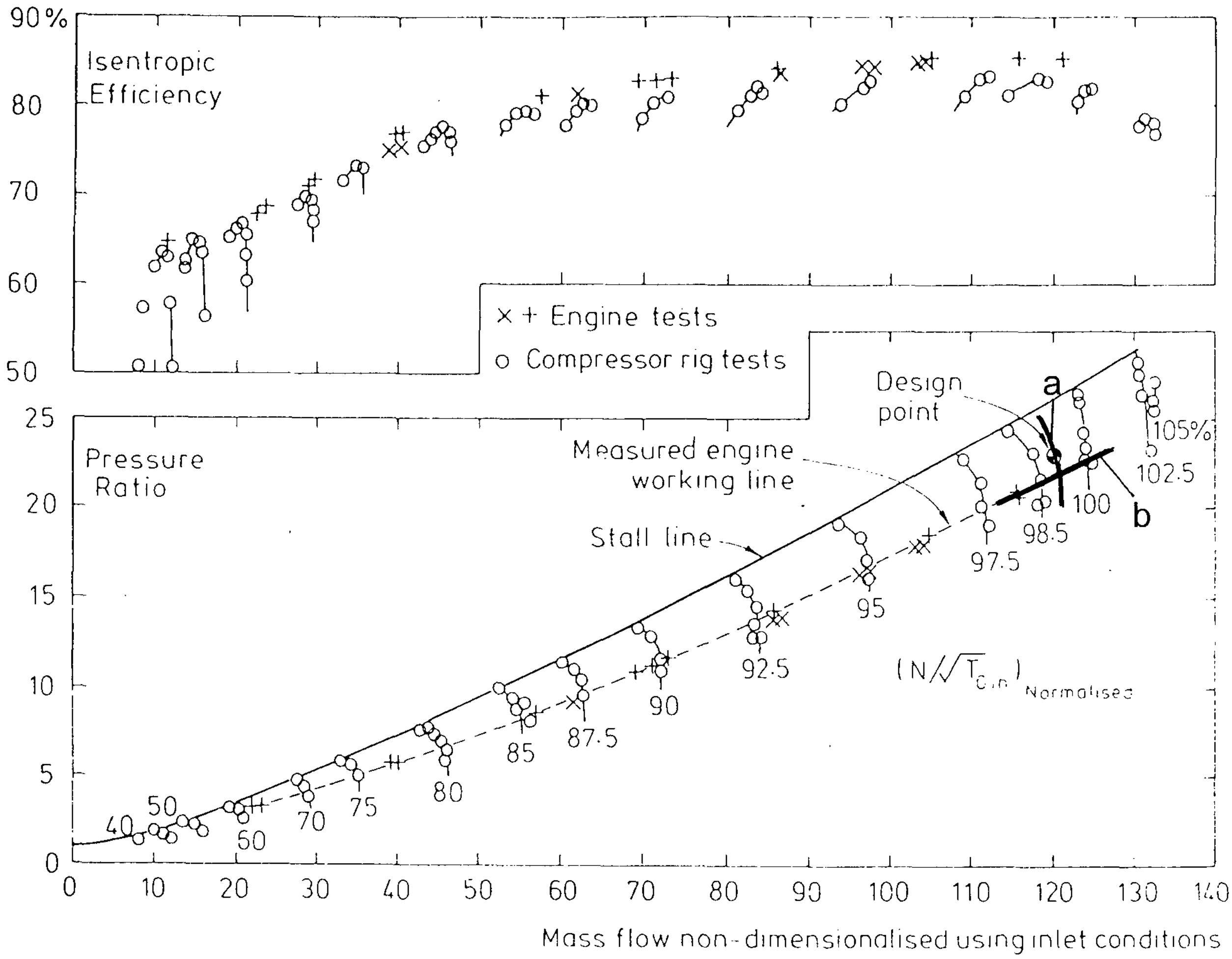

Fig. 4.1: Characteristics of High Performance Multistage Compressor, GE E[3]

the compressor control items, e.g. variable stator vane positions need to be considered.

Special care has to be given to overall stable operation and to proper starting capability. Part speed operation

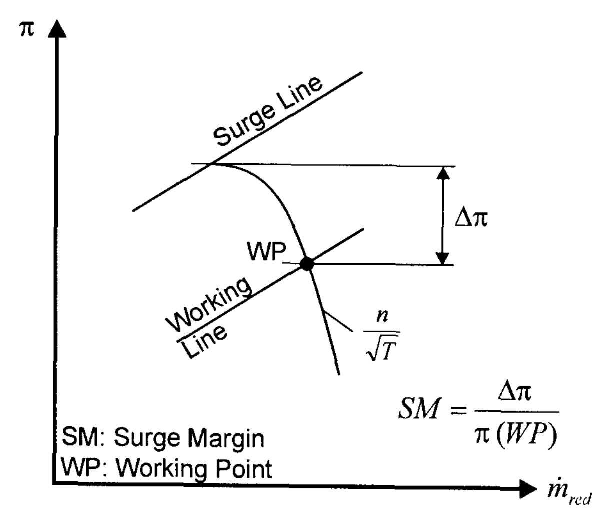

Fig. 4.2: Definition of Surge Margin

of multistage compressors can be improved by handling bleeds at suitable positions and by variable stator vanes for the first stages. Handling bleeds increase the entry massflow, thus unloading the front stages pulling them away from their stability limit. Variable stator vanes change the characteristics of the individual stages.

4.1 Stage Characteristics

In the general aerodynamic considerations of turbomachinery design it is common practise to describe the performance of individual stages by non-dimensionalised characteristics. These maps describe the energy transfer to the fluid and the efficiency of the energy transfer in relation to its flow. Two different ways are in use:

- relative enthalpy rise ψ versus relative axial velocity φ, fig. 4.3.
- pressure rise π versus reduced massflow $\dot{m}_{red}$ fig. 4.4

with:

$$\psi_{ht} = \frac{a}{u_2^2/2} = 2\left[1 + \varphi_2\left(\cot\beta_2 - \frac{u_1}{u_2}\frac{\varphi_1}{\varphi_2}\cot\alpha_1\right)\right]$$

$$\psi_{yt} = \psi_{ht} - \frac{j}{u_2^2/2}$$

$$\dot{m}_{red} = \dot{m}\frac{\sqrt{T/T_{ISA}}}{p/p_{ISA}}$$

Fig. 4.3 describes the stage behaviour non-dimensionalised with circumferential speed. Assuming the relative losses do not change significantly, the characteristic is valid for all speeds. It is usually applied for stationary turbomachinery.

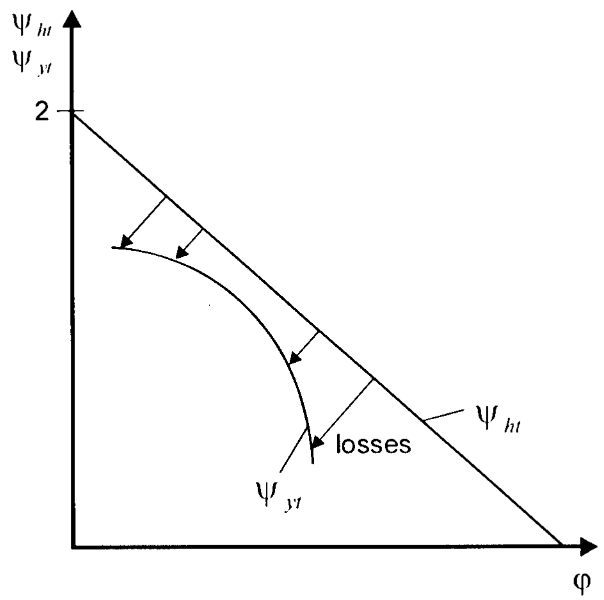

Fig. 4.3: Compressor Stage Characteristic
$\psi = f(\varphi)$

The second form of describing the characteristic is non-dimensionalised with the speed of sound and is called mach-equivalent characteristic. It is usually applied for jet engine components. Here the operating line is dependent on speed. The parameter for the individual speed lines is the reduced aerodynamic speed:

$$n_{red} = n\Big/\sqrt{T/T_{ISA}}$$

In both diagrams the operating range is limited by rotating stall or surge in the upper left corner and in the lower right corner at the maximum massflow by choking in the stage. Properly matching the stages of a compressor implies ensuring that these limits of the stages are not exceeded in the compressor overall operating range.

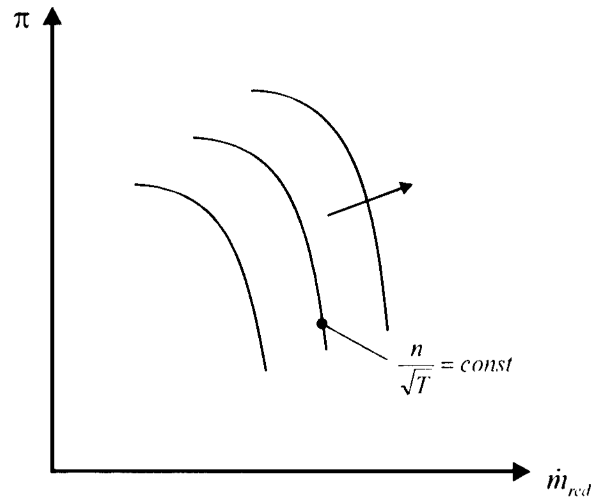

Fig. 4.4: Compressor Stage Characteristic
$\pi = f(\dot{m}_{red})$

4.2 General Considerations for Matching Compressors

The creation of the aerodynamic design requires the selection of two special operation conditions, the so-called *design point* and the *matching point*. It is not unusual that both conditions are identical.

The design point is selected where the compressor operates most of the time or where its performance is of special interest. For multistage compressors with high performance levels, the design point will usually be in the high speed range and close to the maximum achievable pressure ratio, see fig. 4.1. For aero engine compressors with a wide operating range and an excellent and reliable transient performance are required. Here the design point will be selected on or above the intended working line with additional focus on the stability margin. This special requirement sets the boundary conditions for the blading process.

The challenging problem of a multistage compressor is its stagewise matching /4/. At the matching point, the outlet flow conditions of one stage have to fit the inlet conditions of the next stage and each individual stage operates in its optimum. This can only be achieved in one single point. As soon as the multistage compressor is operated at different dimensionless operating speeds or at different massflow rates even on the working line, all stages will deviate from their optima. Therefore, the optimisation of stagewise matching is the key to excellent performance at both design and off-design conditions /5/.

Modern advanced CFD-tools enable the aerodynamic layout of the compressor to be extended from a single point optimisation to a multistage design and to off-design analyses. Here the first step is the investigation of the performance of a single blade row under off-design conditions. Besides lengthy detailed investigations of the velocity and pressure field, simple plots of losses versus change of incidence and Mach number are excellent and fast guides for the aerodynamicists, fig. 4.5. In the meanwhile, real three-dimensional multistage tools are available for multistage analyses, but they still require significant computational time and can not be used for substantial off-design calculations including design iterations.

The general matching behaviour of multistage compressors for compressible fluids will be described in the next paragraph based on a simple model.

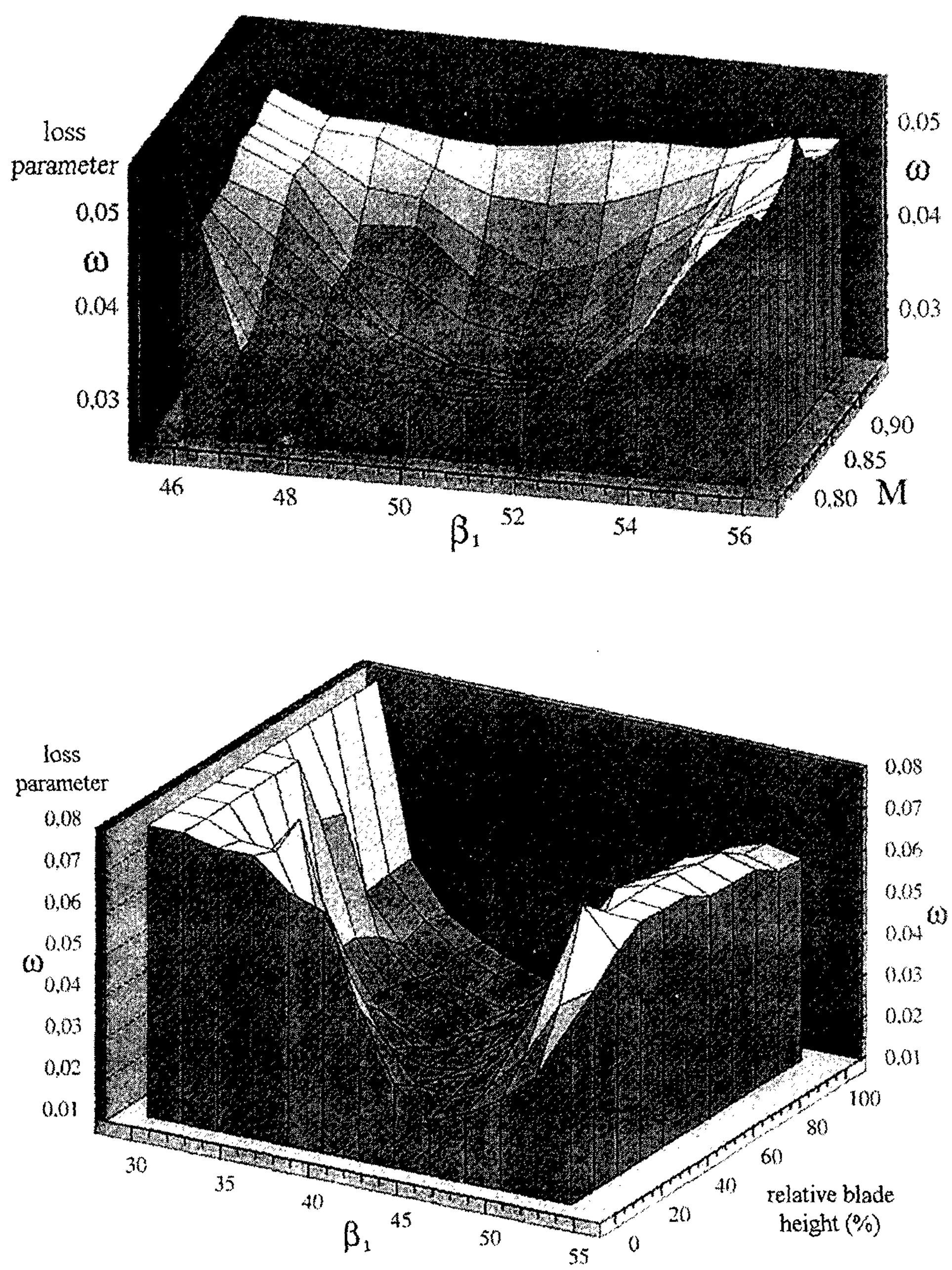

Fig. 4.5: Compressor Blade Losses versus Incidence and Mach Number Variation /6/

4.3 Normal Operating Conditions

The annulus of multistage compressors for compressible fluids needs to have a contraction rate ensuring that with the increase in density the axial velocity of the fluid does not reduce to unacceptable levels. For ease of the following discussion, it is assumed that the design intent meridional velocity stays constant. Fig. 4.6 shows a typical multistage compressor annulus shape, fig. 4.7 our simplified model annulus. The annulus cross sectional area has been matched for a certain rate of pressure increase and of density change. In our model a second simplification is introduced with the assumption of identical characteristics of the stages and that at the design point they operate at the same dimensionless point.

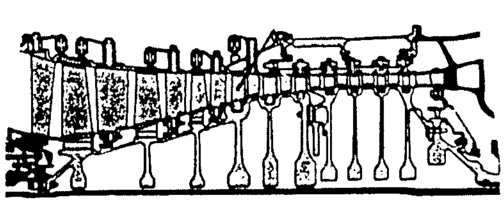

Fig. 4.6: High Pressure Compressor

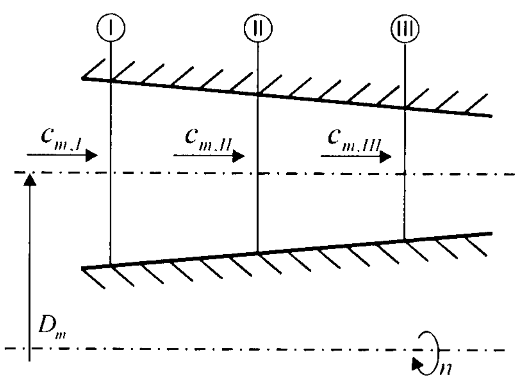

Fig. 4.7: Simplified Compressor Annulus Model

For the discussion of off-design conditions two possible ways of operation have to be distinguished, changing the downstream throttle without change in speed and changing the speed with constant downstream throttle.

4.4 Off-Design Stage Behaviour

The general difficulty in operating multistage compressors under off-design conditions results from the amplifying effect of any deviations in the front stages for the rear stages. Fundamentally, the behaviour can be discussed based on the dimensionless flow coefficient at inlet and outlet of the compressor:

$$\dot{m}_{red} = \dot{m}\,\frac{\sqrt{T/T_{ISA}}}{p/p_{ISA}}$$

and the general stage behaviour, see paragraph 4.1. Compressor stages are operated on the stable arm of the characteristic, which is on the right of the operating point with maximum pressure ratio.

This implies that with a reduction of flow coefficient the pressure ratio increases. For today's high-performance compressors the polytropic pressure increase causes a simultaneous temperature ratio increase which is much smaller than the pressure ratio. Assuming today's efficiencies an exponential relation of 0.3 can be expected.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$$

This correlation means that for modern compressors the pressure increase dominates and the exit flow coefficient reduces even more than the inlet flow coefficient.

For an increase in flow the opposite effect occurs. The stage pressure ratio reduces with a small impact on the temperature ratio and thus the inlet flow coefficient to the next stage increases even more.

4.5 Off Design at Constant Speed

At constant speed, the operating point of a compressor is changed by varying the downstream throttle. Fig. 4.8 shows a schematic map with „a" as the normal operating point. Closing the throttle reduces the massflow and thus increases the pressure ratio, point c in fig. 4.8. This changes the overall operation conditions of each individual stage. The reduced inlet flow drives the operating point of the first stage to higher pressure ratio, reducing the inlet flow to the second stage even more. This effect is amplified throughout the machine, resulting in the largest deviation in the last stage, fig. 4.9. Assuming that at design point „a" all stages had the same stability margin, closing the throttle at constant speed shifts all

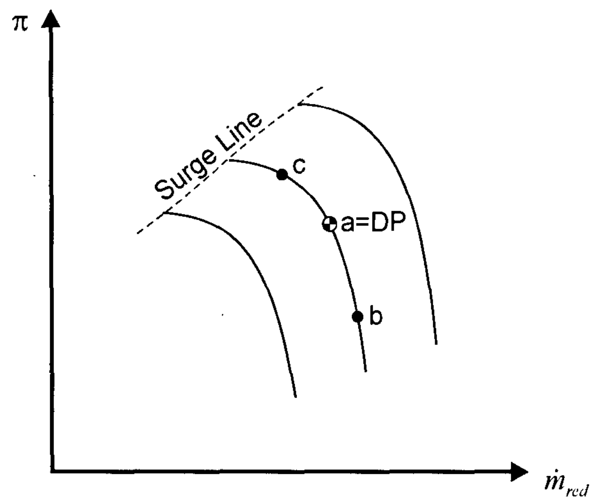

Fig. 4.8: Compressor Map for Constant Speed with Operation at Different Downstream Throttles

stages towards the surge limit, with the last one having the highest deviation, dictating the overall stability of the compressor.

Opening the throttle at constant speed causes the equivalent reactions, but vice versa shifting the overall working point to „b" in fig. 4.8 and unloading all stages. Again the rear stage is the limiting, now approaching choke.

In summary, changing the throttle downstream of the multistage compressor changes all stage operating points similar to one side of the characteristic. The largest deviation is experienced in the last stage.

4.6 Operation at Part Speed

Similar to the previous behaviour, part speed operation of the multistage compressor with the same downstream throttling device or throat area can be explained. The inlet conditions remain unchanged.

Assuming a reduction in speed all stages operate at reduced pressure ratios and hence at reduced density changes. The area match performed in the matching point will not be suitable for this changed condition.

Shown in the form of the ψ-φ-Diagram, fig.4.3, dimensionless with the rotational speed, the first stage operates at reduced massflow with an increased enthalpy rise. The reduction in speed, however, counteracts the increased dimensionless work, and the inlet flow of the downstream stage is slightly higher. This stagewise increase in inlet flow is carried throughout the compressor, see fig. 4.10.

This means that in comparison to the design layout for reduced speed the rear stages will see an increase in dimensionless axial flow, while the front stages, due to

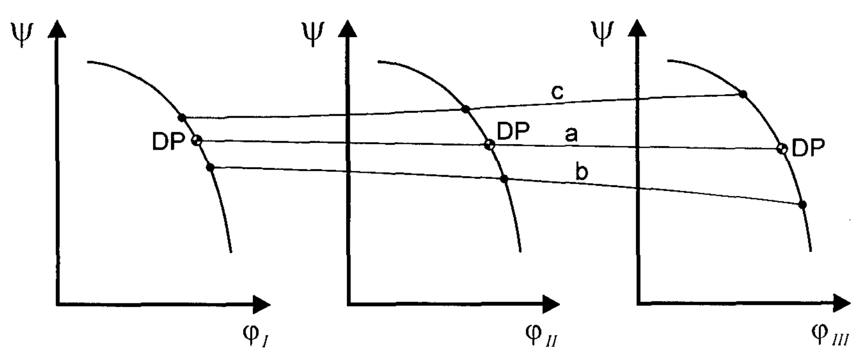

Fig. 4.9: Stage Operation in a Multistage Compressor at Constant Speed with Different Downstream Throttles

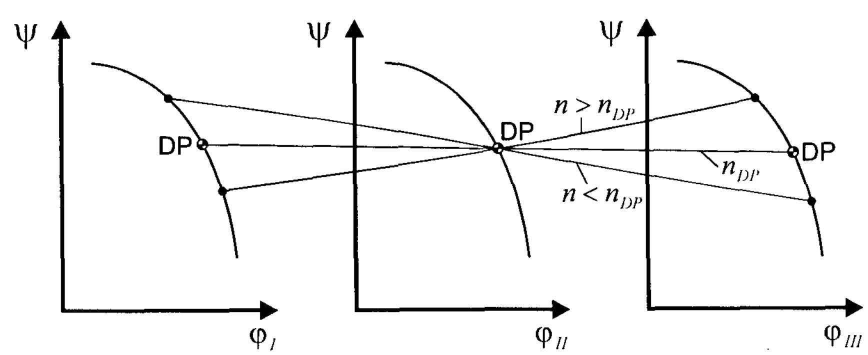

Fig. 4.10: Stage Operation in a Multistage Compressor with Constant Downstream Throttle and Variation in Speed

the overall reduction in flow, will see a decrease in axial flow. In part speed operation the rear stages are loaded less, coming closer to choke, and the front stages are loaded stronger, dictating the compressor's overall stability limit.

For increased speed the matching effect reverses. The rear stages are loaded stronger dictating stability and the front stages are unloaded, fig. 4.10.

This overall matching behaviour of multistage machines has to be taken into account already in the early design considerations. As the design point reflects a high-speed condition, the matching will be chosen with highly loaded rear stages.

Multistage compressors operating at a wider range of conditions, e.g. in jet engines therefore need to be designed in a way that allows the rear stages still operating with the required stability / surge margin at high speeds while accepting a violation of the stability limit of the front stages at low speed. For the compensation at low speed variable stator vanes can be introduced together with the installation of bleed valves. Those are installed at different positions downstream of the critical stages and are opened at low speeds to increase the massflow. This shifts the stage operating points on their characteristics to the right and increases the stability / surge margin by unloading.

5. BLOCKAGE AND TIP CLEARANCE

The general behaviour of the stages and their matching is one of the most expensive challenges in the design of high-performance multistage compressors. Therefore, all parameters of the whole product, influencing the matching under steady and transient conditions, require a careful design consideration. The major contributor is the general aerodynamic design including work distribution, annulus shape and the technology standard of the blading. As described in an earlier lecture, the basic matching between the stages is already implemented in the early one-dimensional model /2/. Additionally the radial distribution of the loading is defined in the streamline curvature program.

Due to the viscous effects on the annulus surfaces, additional boundary layers reduce the available cross-sectional area, fig. 5.1. This effect can be estimated with the blockage factor, based on empirical and experimental data which are proprietary in most companies. It requires careful selection for new designs. The geometric area can simply be increased to compensate the blockage. The blockage factor is one of the most critical assumptions made in the design process, as an area mismatch will immediately set up the intended aerodynamic matching similar to the

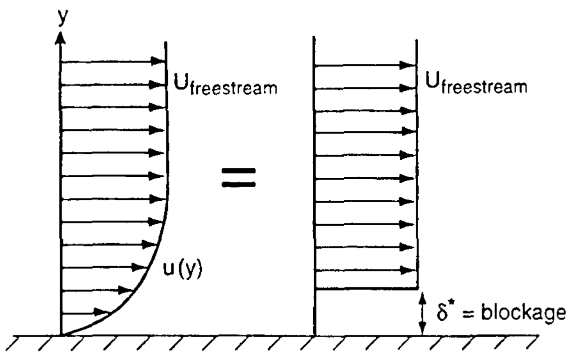

Fig. 5.1: Blockage Schematic /5/

effects of part speed operation and amplified from stage to stage.

A modern methodology for quantifying compressor endwall blockage together with an approach using this quantification is presented in /7/. The results are based on numerical simulations and measurements in low-speed compressors together with simulations in wind tunnels.

All loading considerations assume a certain degree of tip gap. For first design studies certain clearances based on experience will be assumed. In the design process the task changes to ensure that the design intent tip clearance is achieved. This becomes even more challenging with the demand to maintain the matching and the distribution of tip gaps during transient conditions.

6. DESIGN OF TIP CLEARANCE

This part of the lecture aims to highlight the complex multidisciplinary task of designing the compressor parts such that the design intent tip clearance of the high performance multistage machine is achieved.

Large tip clearance has a detrimental effect to efficiency and stability of compressors /8/. Optimum performance is achieved with a minimum level of tip gap, the limiting factor being the mechanical constraints of the design. While several publications on aerodynamic investigations and improvements /11-14/ are available, few discuss the particular standard of the design and hardware.

6.1 Dimensionless Parameter for Tip Clearance

For multistage compressors it is common to describe the overall level of tip clearance by one single value, the *RMS tip clearance*. It uses the root mean square to average all stages:

$$RMS = \sqrt{\frac{1}{N}\sum_{1}^{N}\left(\frac{TG}{BH}\right)^2}$$

with: N: Number of stages
TG : Tip gap
BH : Blade height

A value of RMS around 1% to 1.5% in stabilised hot running conditions is typical of today's multistage compressors.

For annuli with a high contraction rate from front to rear, e.g. with long blades in the front and a small annulus in the rear, this value can only be a useful guide with emphasis on comparisons between similar designs.

The averaging process balances uneven distributions between the stages, which deletes all detailed stagewise information. As has been seen in chapter 4, the rear stages of the compressor are more important for a stable operation than the front. Shifting the distribution between the front and the rear at constant overall RMS therefore causes significant changes in the compressor stability. These limits of use of the averaged RMS value always need to be taken into account.

For multistage compressors besides the overall RMS value the distribution of the relative tip gaps over the stages needs to be looked at. The general application to the whole compressor can be extended to just analyse and compare sections of stages. This turns out to be very beneficial if due to limited instrumentation, e.g. in engine tests, the aerodynamic analysis is based on blocks of stages as well.

The RMS value can be computed for steady and transient conditions, the latter being very sensitive to inaccurate time delays between the stages.

If exposed to transient manoeuvres, local design parameters, heat transfer conditions and e.g. the materiel selection play a significant role. Their interaction and influence is discussed in the following.

6.2 Overview of Main Contributors to Tip Clearance

The aerodynamic layout of high-performance multistage compressors is based on considerations regarding the load distribution and the matching of the blading. For both certain assumptions of the envisaged level of tip clearance have to be made. Designing the steady and transient behaviour of the gap between aerofoil tips and the adjacent casings or rotating walls requires a close and early cooperation of several disciplines. The steady and transient levels finally achieved depend on a multitude of single contributors, whose separate effects are discussed here.

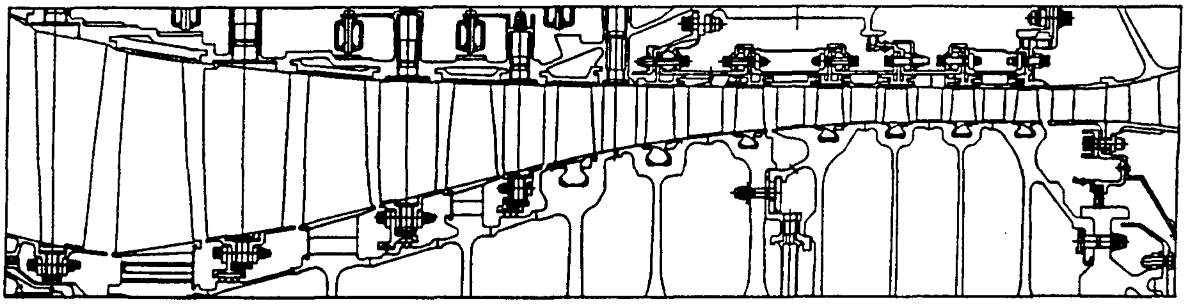

Fig. 6.1: V2500 High Pressure Compressor /15/

Fig. 6.1 shows the cross section of the V2500 ten stage high pressure compressor /15/ as an example of a typical current design. The gap between the rotor tip and the casing of each row depends on local parameters as well as on parameters of the overall engine configuration, both being listed here:

- centrifugal forces,
- axisymmetric thermal deformations,
- special thermal deformations,
- pressure loads,
- rubs,
- grinding tolerances,

- stack up of tolerances,
- bearing tolerances,
- rotordynamic effects,
- manoeuvre loads,
- special instructions for manufacture and built.

These parameters can have an axisymmetric or an asymmetric influence on the tip gap, both reducing the compressor stability limit. Asymmetric gaps can rotate with the rotor, e.g. bowed rotor drums, or remain at a position constant relative to the casing, e.g. deflections due to manoeuvre loads. Therefore, detailed investigations of tip clearance behaviour have to consider the spatial effects.

The following discussion of influencing parameters is based on multistage compressors for jet engines. Their environment includes fast transients, significant ambient temperature changes and g-loads. The interaction of the effects can directly be transformed to stationary compressors.

6.2.1 Centrifugal Forces

Centrifugal forces act on all rotating parts. They depend on speed, radius and mass. Centrifugal forces increase with the square of the rotational speed and do not experience any time delay against changes in speed.

$$F_{CF} = m\frac{\omega^2}{r}$$

Therefore, small deviations from the design point will cause large deviations of centrifugal forces. All rotor discs and shafts experience radial elongations, in approximation axisymmetric elongations. Blades are deformed depending on their shape, but in general they experience radial elongations similar to straight beams.

The centrifugal forces are beneficially used to ease the assembly of the compressor. As they act on the rotating parts but not on the static ones, the cold built clearance is always larger than the running clearance, making the complete casing assembly a less difficult task. In addition no special fixture for the blade position is required. Under static conditions the blades move loose in their root fixings. They will find their final position when the rotation reaches a certain value and the centrifugal forces dominate the individual weights. Detailed dynamic measurements showed that the blades find an individual and non-repeatable position from each run. The blade tip position therefore always varies in a final scatter band. Unfortunately this is also the case for the positions the blades have during the final tip grinding process. Therefore, although the final grinding process eliminates all global tolerances of the fit blade root to disc groove, the tolerances on both determining the freedom of finding the forced position still remain.

6.2.2 Axisymmetric Thermal Deformations

The compression of gaseous fluids changes the temperature of the fluid, the temperature ratio is directly coupled to the pressure ratio by the polytropic correlation. High temperatures require the use of materials with a higher thermal capability than Nickel based alloys have, increasing the material cost. Thermal loads are introduced into the parts by the temperature fields on the surfaces and by the development of internal temperature fields through heat transfer and conduction. The temperature fields have two coupled effects:

1. thermal deformations or elongations of the parts in radial, circumferential and axial direction,
2. creation of stresses in the parts.

Depending on the design, it is possible that around 50% of the overall mean stress is caused by thermal loads.

Thermal loads are already present under steady state conditions, but more complicated scenarios are created under transient manoeuvres. The change in tip gap is the result of the widening of the casing minus the elongation of the rotating parts taking into account the cold built clearance and the effects of centrifugal forces, fig. 6.2. It can easily be influenced by the material selection and the material matching between rotor and casing. The tip clearance change during thermal elongation is the small difference of two large numbers, making its prediction extremely difficult. This problem is amplified by the fact that the heat transfer discretisation models including the internal air system models do not yet have the necessary standard of reliability.

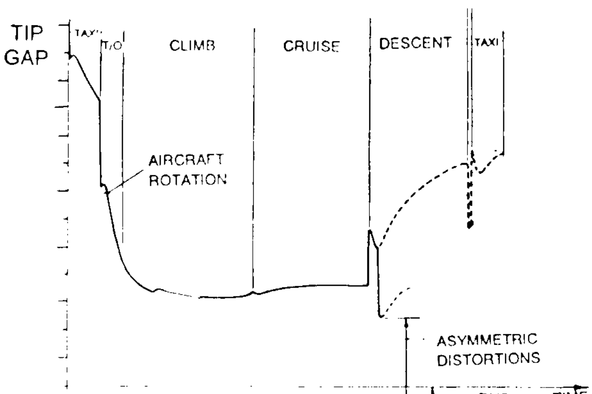

Fig. 6.2: Change of Tip Clearance due to Centrifugal Forces and Thermal Effects

For steady state conditions all temperature fields in rotating and static parts are fully developed and cause the complete structure to deform in a specific way. This is usually an axisymmetric deformation as the temperature field can in first approximation be assumed to be axisymmetric. But locally mounted accessories or bleed ducts create local changes in heat transfer and mass distribution and cause local temperature gradients with geometrically asymmetric effects.

For transient conditions the local heat transfer and the mass distribution play the dominant role. The transient transfer from idle to high running conditions will be discussed as an example.

At idle the compressor operates with low pressure ratio. As the annulus is designed for high running conditions, it does not provide the correct area ratio for the small change in density. Therefore, high amounts of handling bleed in the front stages are required. These are collected in manifolds, which heat up the inner compressor casing from the outside and are locally fed into pipework outside the compressor. With the increase in speed the pressure ratio and thus the temperature in the compressor increase as well. Local heat transfer ensures that the temperature of adjacent parts increases. Due to the high mass of the rotors and their small contact area to the annulus, their temperature will go up slowly. The thin casings have a much higher ratio of contact area per mass and will heat up much faster. This might be supported additionally if customer or handling bleed is taken, increasing the Mach number on the outside of the casing. During this transient the casing diameter increases faster than the rotor diameter, causing a significant change in tip clearance and thus a significant reduction in compressor stability margin. It is the task of the multidisciplinary design team to optimise the transient thermal behaviour of the compressor. Some typical influence parameters are:

- thermal barrier coating on casing parts,
- improved heat up of rotor drum via internal air system,
- heat shields and insulation in casings,
- thermal throat areas in casings,
- changed mass distribution including stiffening cold flanges,
- reduction of the influence of local singularities as bleed ducts,
- position of working line,
- acceleration control.

Thermal elongations operate into axial direction as well. Both casings and rotor change their length depending on the selected materials and the local temperatures. The relative movement has to be taken into account for the cold dimensioning of the axial gaps between the blades and vanes, and additionally will change the tip clearance in areas of high annulus contraction, which means in areas of steep annulus lines, fig. 6.3. Here a small change in axial position causes a large change in tip clearance. This interaction has to be understood well and known in the early design studies.

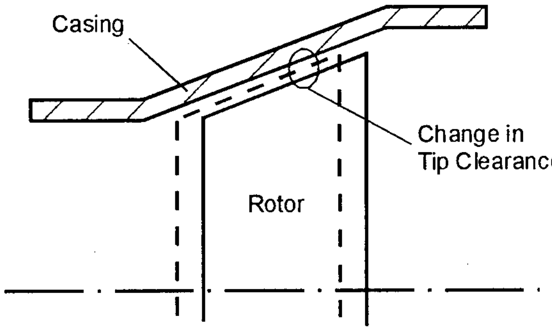

Fig. 6.3: Influence of Axial Movement on Tip Clearance

In the case of the V2500 the rear outer annulus wall is nearly at constant radius, fig. 6.1, and axial movements do not have significant effects. The fixed bearing is in the front of stage 1. At the inner radius of the annulus in the steep front stages, the variables have inner shrouds, which have separate sealing against leakage designed to work under different axial relative positions. In the rear stages, the annulus is flatter and an axial movement does not have an impact on the tip clearance of the highly loaded stages.

Some further hints are required concerning the prediction of thermal behaviour. Excellent tools are available for the numerical prediction of thermal displacements and thermally caused stresses. Like with each computational tool, the results do not only depend on the tool itself, but on the discretisation of the geometry and the description of the boundary conditions. Especially the latter item is extremely difficult for thermal aspects. Before any measurement is known, the flow pattern in the internal air-system has to be estimated, in addition the local heat transfer coefficients have to be calculated based on the local velocities. Geometric simplifications might have significant unrealistic effects on the calculated and estimated results.

6.2.3 Special Thermal Deformations

Axisymmetric thermal deformations under running conditions were discussed in the previous paragraph. Thermal turbomachinery components experience additional thermal effects after usage. When the engine is stopped, the circumferentially uniforml thermal distribution of the fluid changes by natural convection. The hottest fluid collects in the upper part of the engine warming up the casings and rotor, the

colder fluid is dropping into the lower half. Already after a short period of time this causes the engine to distort into a sort of banana shape. Rotor and casings will bend upwards simultaneously. Problems occur as soon as the rotor begins to rotate again. With its banana shape the tip clearance will be reduced with each degree of rotation. Depending on the severity of the banana shape, the rotor might rub into the deformed casing and might finally be blocked. If being rotated further by force, the blading will be seriously damaged with a simultaneous loss of performance. This so-called *rotor bow effect* can be overcome by a special control or instruction ensuring that the rotor is turned regularly during the cool down phase or simply by specifying the minimum stop and cool down duration.
If the engine is started with a bowed rotor, which has not exceeded the critical dimension, this special effect does not change tip clearance behaviour, but has a significant effect on the vibrational behaviour in the starting phase until the thermal gradients have stabilised again.

6.2.4 Pressure Loads

The primary task of a multistage compressor is the reliable delivery of a given massflow with a high pressure ratio and an excellent efficiency at low cost with a small number of stages. The pressure increase is achieved by the blading in the annulus and causes pressure loads on all parts. Its effect on the rotor drum is insignificant in radial direction. The change of diameter of the casings is less important in stationary multistage compressors with high wall thicknesses, but its effect on the tip clearance has to be taken into account in aeroengine compressors, where for weight reasons the casings are extremely thin. In areas of high pressure difference between inside and outside, ring casings are preferred to split casings, which tend to deform non-uniformly. Besides the pure radial movement, additional axial movements, caused directly by pressure loads or indirectly by angular deformations of flanges, have to be considered.

Due to the contraction of the annulus on tip clearance, the resulting axial force determining the bearing load has a significant influence on the overall engine. One aspect, which will not be discussed in the content of this lecture, is the effect of the loading and its direction on bearing life.

The axial position of the rotor is more important in the context of its relation to the casing. On the one hand, it depends on the axial thermal elongation of the rotor relative to the casing, as already mentioned above. On the other hand, it changes if the loading direction of the bearing alternates, which might occur in the lower speed range. In a steep annulus this has a significant influence on tip clearance, fig. 6.3.

6.2.5 Rubs

In many cases multistage compressors are designed such that a complete closure of the tip gap under certain conditions is allowed. With a further extension of the aerofoils or the rotor drum a grinding process between the touching materials starts. Depending on the selected materials, the rubs reduce the aerofoil length or the opposite liner is abraded. Both cause a permanent increase in tip clearance.

It is important to recognise that an asymmetric eccentricity of the rotor can cause an axisymmetric increase in tip clearance by the aerofoils grinding into the casing liners. One example thereof is a bowed rotor in a non-bowed casing. With the acceleration the centrifugal forces increase until the tip gap locally becomes zero. This zero gap rotates with the rotor. Now two scenarios are possible for further acceleration:

1. If the rotor material is harder than the abradable, the local rub will rotate with the rotor and cause a 360 degree uniform increase in tip clearance. This increase even remains after the rotor has thermally stabilised.
2. If the rotor material is weaker than the abradable, then it locally grinds the blade to a smaller size and therefore to a smaller rotor diameter at this position.

The damage to the compressor differs significantly from the first case. After thermal stabilisation the tip clearance will only be larger in one circumferential position rotating with the drum, which can be assumed to have less negative effect on compressor stability.

6.2.6 Grinding Tolerances

The final cold built clearance is achieved by the grinding process of the rotor and vane tips and of the according rotor and casing liner paths. Grinding technologies of different complexity and thus costs are available in industry. The higher the compressor performance and the smaller its size, the more accurate in absolute numbers the grinding result has to be. For aero engines it is common practice to grind the complete rotor assembly and the complete casing assembly fixing the assemblies at the real bearing positions or even the final bearings to compensate for the stack up of mechanical tolerances. The specified mean grinding diameters are based on a combination of prediction and experimental experience.

A major decision is the usage of matched pairs versus free exchangeable rotors and casings. For matched pairs, the rotor or the casing is ground first. The measure finally achieved, which without saying should be within the given tolerance band, will be measured with utmost precision, and be the basis for the nominal grinding diameter of the second assembly, the casing and the rotor respectively. Matched pairs eliminate the occurrence of two tolerance bands for the tip clearance fit, but create additional costs of maintenance and product support.

During the grinding process of any aerofoil tip, whether blade or vane, it has to be ensured that it sits in its running position. The latter depends on the geometry of the root and on the acting pressure and on centrifugal forces. Complicated tools and processes have been developed, which more or less support this demand.

For the grinding of the vane tips, special fixtures have to be used to hold the vanes in the running position. A simple method is to fill the spaces with wax, building a complete ring. Investigations showed that some vanes became loose during the grinding process and others were fitted unproperly from the beginning. Unfortunately, as soon as the wax is applied to the vanes, the root position is no longer visible for control purpose. However, this method has the advantage of simple processes. A significant improvement in quality and in process time can be achieved using reliable, specially developed mechanical tools.

A different approach is used for the rotor tip grinding process, which is performed on a combination of grinding and balancing machine. The assembled rotor is spun with a certain speed. With increasing speed the blades find their natural position due to centrifugal forces. The forces introduced by the grinding process at the tip will erode the position of the blades and therefore impair the quality of the final result. During the grinding process the balancing needs to be checked and corrected to ensure minimum rotordynamic influences.

With the introduction of high speed grinding machines higher speeds can be achieved, aiming at improved positional control of the blading, but at the same time additional challenges are introduced. The higher the rotational speed, the higher the required driving power for the fully bladed rotor, which for simple applications rotates under atmospheric conditions. Due to the size and weight of the rotors, the individual rotordynamic behaviour of the combination rotor and grinding machine has to be considered. The dynamic vibrations can easily be in the order of the finally required radial tolerance. For high speed grinding machines on-line measurement of the vibrations and of the achieved diameters is advantageous.

6.2.7 Stack-up of Tolerances

Multistage compressors are built with a high number of parts. The final non-running position of the rotor relative to the casing, often referred to as cold position, is the result of the tolerance chain from the casing through the bearing and the rotor assembly. During the detail design, all parts and their fits are specified with dimensional and positional tolerances. At this time it is unknown with what quality the individual parts will be manufactured, and whether statistically their shape will reflect the design intent medium position, or if the parts for example for ease of manufacturing processes will be produced to one side of the tolerance band. To avoid late surprises, an intensive discussion between design and manufacturing is required, especially taking into account the limitations of the manufacturing methods. Each assembly of any compressor will be a unique built with unique shapes and unique deviations from design intent. The final tip grinding process eliminates most of the tolerances and ensures the intended tip clearance level.

To support the detail design a stack up of all tolerances under cold conditions should be done. This will show the maximum possible deviation from the ideal position and, with a statistical approach, can show the likeliness of assemblies with high deviations. The high number of parts and fits is beneficial for the final quality, as some deviations will counterbalance each other. The stack up of tolerances is particularly important for the rotor drum, as extreme angular deviations will influence the rotordynamic behaviour.

Further improvement can be achieved with special built instructions, which, after the important dimensions of the final parts or assemblies have been measured, prescribe the way of further assembly. One example for this is the clocking of ring casings to avoid banana shapes.

6.2.8 Bearing Tolerances

Bearings are the interface between rotating and stationary parts. Their tight tolerances under loaded conditions contribute to the total tolerance stack up and can be included in the above-mentioned statistical analysis. Bearings with oil damping lead to an additional radial gap, which under running conditions is filled with pressurised oil. Due to the heavy weight of the drum and the dynamic build up of the oil film, it is unlikely that the bearing will centralise. It will rather find a position which is slightly angled from the bottom dead centre, causing the rotor to run non-concentric in relation to the casing creating a large tip clearance on one side and a small one on the opposite side. Without corrective action the stability limit of the compressor would be reduced. Based on design considerations, calculations and measurements, the housing for the bearing can be corrected by eccentric manufacturing, which increases performance but at the same time adds costs to the product.

6.2.9 Rotordynamic Effects

Rotating assemblies of significant size, weight and speed require a thorough balancing procedure. In addition to the structural requirements, the operator may require further reduced vibration levels to improve cabin comfort. The quality of the balancing has already been mentioned in context with the grinding process. As soon as local mass distribution changes, the rotordynamic behaviour is influenced. Therefore, high speed grinders are often combined with balancing machines.

The rotordynamic behaviour of the multistage compressor assembly is dependent on the internal mass distribution, damping and stiffness as well as on the engine mounts. Even with an excellent balancing, certain changes of tip clearance will occur during running. It causes locally increased gaps that have a negative effect on the stability of the compressor.

6.2.10 Manoeuvre Loads and Deformations

Multistage compressors in aeroengines experience manoeuvre loads of significant strength, especially in military applications. These loads can reach around 10 times the gravity, bending the rotor within the differently reacting casing. The process increases the tip clearance in an asymmetric way, reducing aerodynamic stability accordingly. As it can be assumed that these loads mainly occur under critical flight situations, e.g. take-off rotation, or in military operation in situations were full operability is required, only a small degradation of surge margin is acceptable.

The schematic cross section of the BR700 engine shows the important influence of the bearing concept, fig. 6.4. On the high pressure spool the axially fixed bearing is in front of the compressor, the second bearing is behind the high pressure turbine. The highly loaded stages, which at high speed operate closest to the stability limit, are the rear compressor stages. In this concept they are right in the middle between the bearings and experience the largest bending deformations of the rotor. Early special design considerations are required to ensure the full functionality of this concept. The design can be supported by numerous computations with a whole engine model, being capable of a full simulation of the deformations.

The design of the engine mounts on the aircraft has another major influence on engine deformations. Depending on the mounts' stiffness, identical manoeuvres introduce significantly different external loads to the system.

The required prediction of the mechanical deformation needs special attention. Modern computational tools allow the simulation of complete aeroengines for structural investigations, Fig. 6.5. The engine is described with finite elements, the detail has to be suitable for the purpose of the calculation. During the design cycle, the model is constantly updated and refined. It is suitable for a number of calculations. The effect of external, multi-gravity forces on the engine and its deformation and the optimisation of the mounting concept are only few applications. Early investigation of rotordynamic behaviour allows the overall optimisation of the design in this respect. For aeroengines an additional application is the prediction of fan blade-off effects, forces and resulting damages.

As far as tip clearance behaviour predictions are concerned, it has to be highlighted once again that their change is the small difference of large deformations of rotor and casing separately requiring an accurate reflection of the mechanical characteristics of the detailed design.

These models are already extremely complex only reflecting the mechanical behaviour under structural loads and external forces. With growing computational capability, they need to be extended to reflect the multidisciplinary nature of the product. As a first step, thermal loads have to be integrated even though linear superposition is a good approximation. As a further

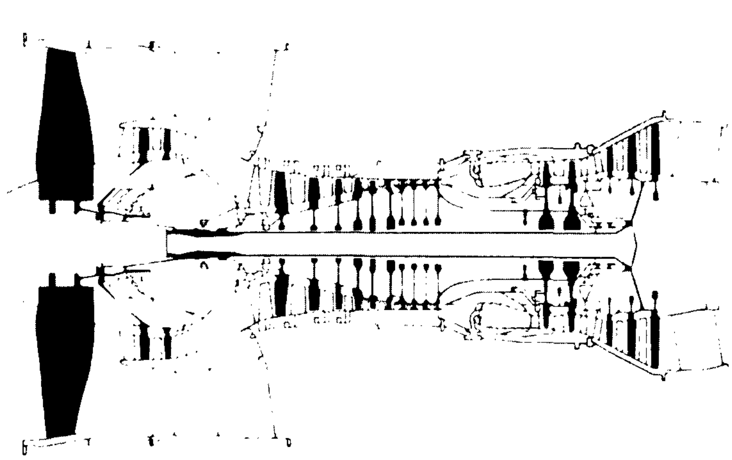

Fig. 6.4: BR700 Schematic Cross Section, /16/

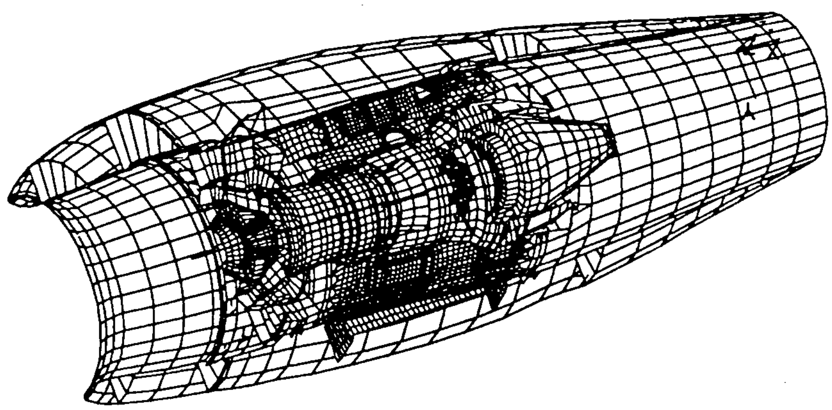

Fig. 6.5: Whole Engine Deflection Simulation with Finite Elements /1/

step the refinement of the model to a degree currently only used for detailed investigations on single parts can be thought of. This could provide a functionality for structures equivalent to the electronic mock-up for design considerations with a tree structure guiding through the individual levels of detail. But going this far, the clear requirement is made that in a proper multidisciplinary approach both models, the design tool and the structural tool, should use the same and therefore consistent data base. In the next step they should be integrated into one single tool.

6.2.11 Special Instructions for Manufacturing and Assembly

Each part is manufactured according to a specific drawing, which among other information specifies tolerances. The manufacturing quality finally achieved depends on numerous factors, the interpretation of the drawing by the manufacturer is only one of these. Certain improvements can be achieved if a number of parts are put together to sub-assemblies and their external interfaces are finally machined together, eliminating the influence of internal tolerances. The disadvantage of this procedure is a more complicated assembly and reduced interchangeability of parts, also increasing the cost of maintenance and product support. Typically the rear inner rings of high pressure compressors belong to this category. Their inner radius is ground after assembly to improve tip clearance.

A second common approach is the creation of matched pairs, which complicates the assembly process even more. The grinding of the annulus and aerofoil diameters were discussed above as an example.

7. Example of Interdisciplinary Design

The importance of multidisciplinary design can be demonstrated best by a typical example. For this purpose, the process of thermal matching of rotor and casing for transient behaviour has been selected, which continues to be one of the most important challenges in compressor design. Several aeroengines have been subject to performance inadequacies requiring expensive corrective actions.

As has been discussed earlier, the basic aerodynamic design is based on a predefined degree of tip clearance. Changes in tip clearance effect the matching and degrade stability and performance. This change of tip clearance during transient manoeuvres is not only caused by the centrifugal forces but by the different timely behaviour of rotor and casing in one stage. This is the result of very different masses, heat transfer

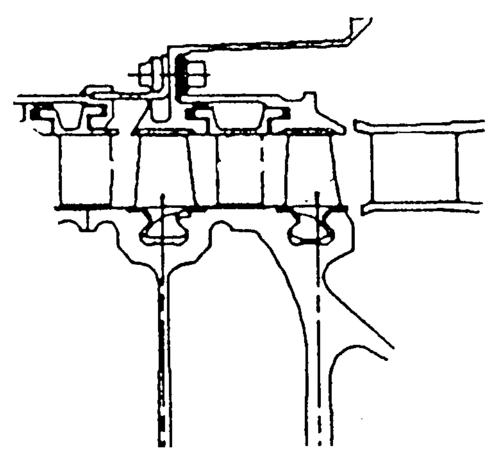

Fig. 7.1: Preliminary Design of Compressor Rear Stages

conditions and surrounding temperatures. Early design investigations have to ensure that the design is adequate for the transient requirements /17/.

Fig 7.1 shows the preliminary design of an inner compressor ring casing of the last stage of a high-pressure compressor. The design was derived from proven design solutions with a strong demand for cost reduction. The result is a significantly simplified casing structure, where previously separated casing rings were combined into one part. The number of splits has been reduced to the minimum, with one split per vane row, which remains to enable the feeding of the vanes into the compressor. In addition, the sealings of bleed slots and manifolds were combined with the naturally required flanges between inner and outer casing. This resulted in the mounting of the last ring of the casing to the previous stage via a flange, which simultaneously carries the connection to the compressor outer casing, the rear end is open towards the diffuser.

It could be predicted that with the above-described design the performance of the compressor degrades significantly during transients. Thermal transient analyses showed a large opening of the tip clearance of the last stage, which was amplified by several parameters. First of all, the cantilevered design had a weak shape at the exit, secondly the mass of the ring was small and could be warmed up in a short time period, and thirdly during an acceleration the cavity outside the last stage ring was filled with hot gas, additionally warming up the ring from the outside.

The multidisciplinary analyses included the prediction of the influence of tip clearance increase on the overall stability of the compressor. For the description of the stage behaviour, the speed independent ψ-φ-diagram.

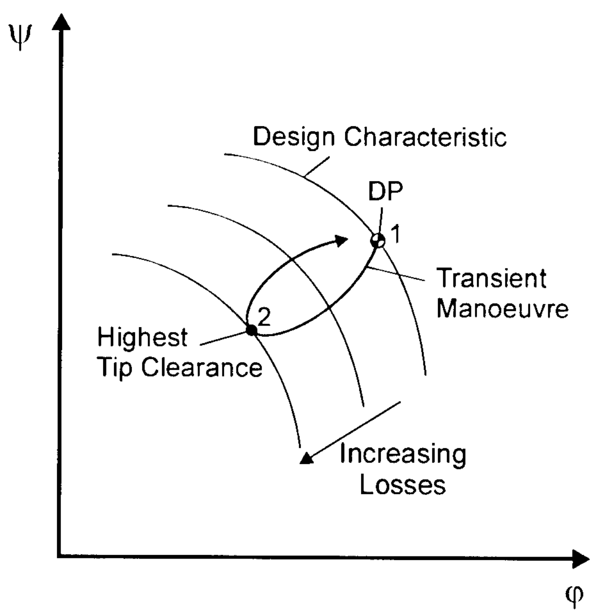

Fig. 7.2: Change of Stage Characteristic with Tip Clearance Increase

which was introduced in paragraph 4.1, is suited best, here see fig. 7.2. For all speeds, the stage should operate on its speed independent characteristic line. But increased tip clearance does increase the losses and the ability of the stage to transfer energy into the fluid, shifting the characteristic to the left.

Based on the ψ-φ-characteristic of the stage and on a simulation of the influence of increasing tip clearance, the overall influence on the stagewise matching can be simulated accordingly. Vice versa, if transient measurements of the compressor stagewise or block-wise matching are available, the change in tip clearance can be derived.

For compressors with limited instrumentation, a detailed block matching analysis can be performed based on pressure measurements in front of and behind the compressor and in the available bleed ducts.

A full acceleration cycle can now be simulated by using fig. 7.2. The compressor starts on the design intent characteristic, marked "1". During the acceleration the tip clearance opens as the casing grows and the characteristic moves to the lower left, indicating higher aerodynamic losses and a loss in pressure rise and flow. The largest excursion is examined after some time, typically 10 to 60 seconds, and marked "2". Its position depends on the degree of additional tip gap. Following this, the discs start to pick up the higher temperature and increase in diameter. Then the tip gap continuously becomes smaller until stable operation is achieved. This is simulated by the characteristic moving to the right again, until it reaches the original position. The effect on the loss of stability margin can easily be derived from a stagewise stacking program.

The analysis showed an unacceptable transient performance of the overall compressor based on the non-optimised thermal matching of the casing to the rotor in the single rear stage. Now the interdisciplinary team was given the task to develop an improved solution.

Once the cause was identified, it was decided to optimise the casing design and not to implement any changes to the rotor. Basically, the following improvements could contribute to the solution:

1. slowing down the temperature increase of the casing by simply adding mass,
2. sealing the cavity,
3. introducing throat areas for the heat transfer,
4. adding mass in cold areas,
5. thermal coating of the involved parts,
6. change of casing material.

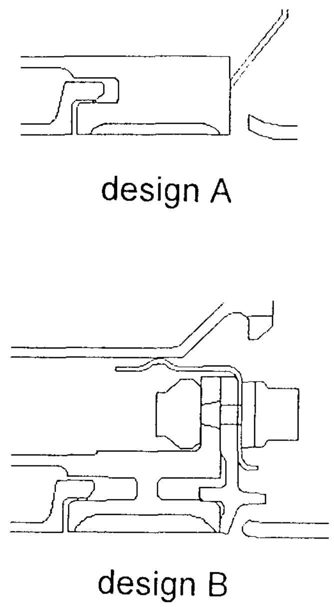

Fig. 7.3: Improved Rear Casing Design

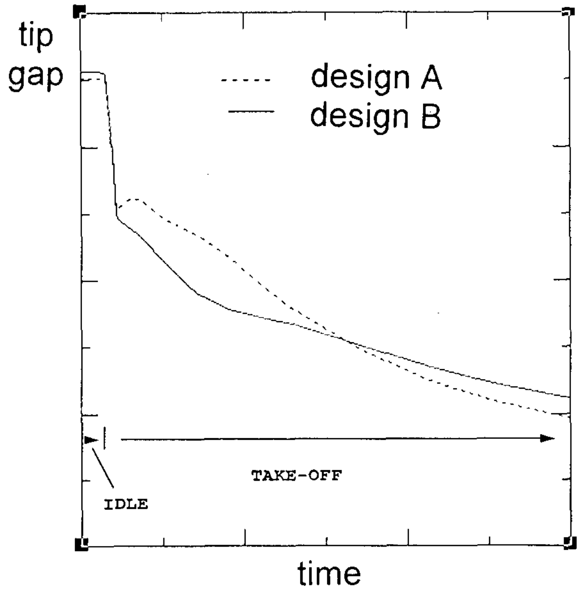

Fig. 7.4: Comparison of Tip Clearance Behaviour of Designs of Fig. 7.3

Several solutions were investigated, fig. 7.3 shows two of them.

Solution A is the simplest change. The mass of the casing ring is significantly increased. Additionally to reduce the heat transfer on the outside of the ring, a heat shield has been introduced, being mounted on the outer flange. Numerical predictions showed a significant reduction of tip clearance overshoot compared to the original solution. But additional improvements were possible.

Solution B provides a thermal behaviour which is far better. Instead of simply adding mass, a complete additional flange was added at the weak rear end, carrying two heat shields. One consisting of thin sheet metal prevents hot gas ingestion into the rear cavity. The second heat shield is a complete ring with two functions. Its special shape at the annulus diverts the hot gas towards the combustion chamber and significantly reduces the heat transfer to the rear casing and to the newly introduced bolts. Its front fit seals the casing ring against the hot annulus gas and eliminates bending of the inner casing path. The heat flux from the annulus into the casing is reduced by the introduction of a heat throat area in the inner casing ring. It basically separates the inner casing ring from the outside and ensures a slower reaction of the outer mass.

The second solution has proven to provide the transient behaviour required for excellent performance. Fig. 7.4 compares the predicted tip gap closure of both solutions, showing that the thermal overshoot was eliminated completely.

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First Order Manufacturing Constraints & Requirements
Design To Cost and Manufacturing Process Considerations

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- *Effect of Tolerances*

MWB 1

In this session of the lecture series we will discuss the impact of cost as a design parameter. Historically in aircraft engine design up until the beginning of 1990, technology drove the design and cost was merely a resultant. With the end of the Cold War and the unprecedented airline losses in the early 1990's, cost shifted from being merely a resultant to a design parameter comparable with weight, specific fuel consumption and thrust. If we define

Manufacturing Cost + Contribution Margin = Sell Price

and Contribution Margin - Fixed Cost = Operating Margin

Downward pressure on Price from the customer and the need to maintain Operating Margin for the shareholders leaves Manufacturing & Fixed Costs as the only variables. The effects of this were felt, not only in the manufacturing area, but also in engineering with the resulting trend to move to more technologically conservative robust designs.

Paper presented at the RTO AVT Lecture Series on "Integrated Multidisciplinary Design of High Pressure Multistage Compression Systems", held in Lyon, France, 14-15 September 1998; Cologne, Germany, 17-18 September 1998; Cleveland, USA, 22-23 September 1998, and published in RTO EN-1.

Life Cycle Cost & Affordability

Life Cycle Cost typically represents the cost of the subsystem (propulsion) over the product's life including Development, Production & Deployment, Field Support, and Disposal; recognizing each phase is typically funded separately.

Affordability considers system costs including system integration (inlet, nozzles, vectoring, controls, signature) and the logistics tail (footprint, reliability, availability) to optimize system cost.

Can the customer afford the product with a predicted level of effectiveness?

LLL 2

Life Cycle Cost typically represents the cost of the subsystem (propulsion) over the product's life including Development, Production & Deployment, Field Support and Disposal; recognizing each phase is typically funded separately.

There are many definitions of affordability. The one we will consider is:

Affordability considers system costs including system integration (inlet, nozzles, vectoring, controls, signature) and the logistics tail (footprint, reliability, availability) to optimize system cost.

Each of these costs are interdependent and usually reducing one will impact the others.

The question is:

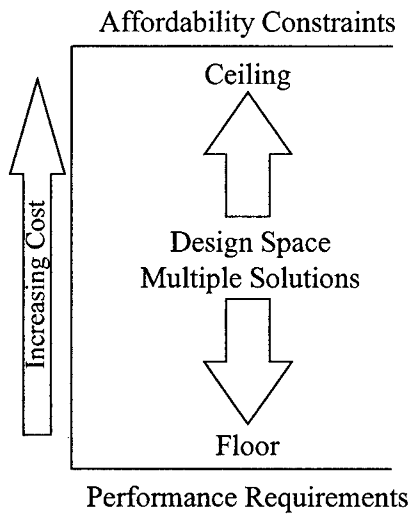
Can the customer afford to procure and deploy the product with a predicted level of effectiveness?

Requirements Versus Constraints

Performance Requirements define the minimum acceptable solution. This is considered the floor of the Design Space.

Affordability (what the customer can spend) provides an opportunity to maximize the design. These cost constraints define the ceiling of the Design Space.

The area between the Performance floor and Affordability ceiling is the Design Space.



LLL 3

Performance Requirements define the minimum acceptable solution. This is considered the floor of the Design Space.

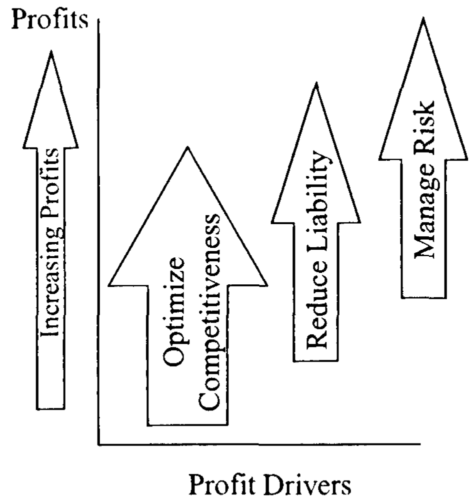
Affordability (what the customer can spend) provides an opportunity to maximize the design. These cost constraints define the ceiling of the Design Space.

The area between the the Performance Floor and Cost Ceiling defines the Design Space where multiple solutions exist.

Supplier Profit Margin

Supplier needs to know the real cost and performance to assess:

- Competitiveness:
  - Performance
  - Acquisition Cost
  - Supportability
- Liability/Warranty:
  - Safety & Reliability
  - Performance
- Risk:
  - Schedule, Technical, Cost

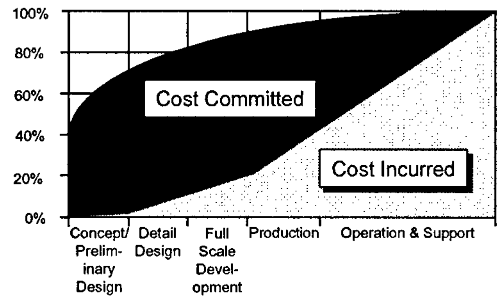


LLL 4

The supplier needs to know the real cost and performance to assess his position in the market place. Competitiveness is driven by Performance, Acquisition Cost and Supportability. Net Present Value Analysis may suggest that Acquisition Cost is more significant than Supportability and its associated costs. The supplier needs to balance Liability and Warranty costs which are driven by Safety & Reliability and Engine Performance against Development and Acquisition Costs. Implicit in this whole approach is risk relative to Schedule, Technical Requirements and Cost.

Cost as a Design Parameter

- Conceptual/Preliminary Design sets 70% Engine Cost for 1%of LCC
  - Engine Configuration
  - Number of Stages & Spools
    - Dimensions, Aero flowpath
    - Bearing/Sump Configuration
  - Design Life
  - Material Selections
  - Performance Requirements
    - Cycle Temperatures
    - Cooling Flows



- Preliminary Design Best Opportunity for Cost Reduction
  - Cost reduction at low investment
  - Ability to change all components
  - Engine architecture is flexible
  - No hardware changes required

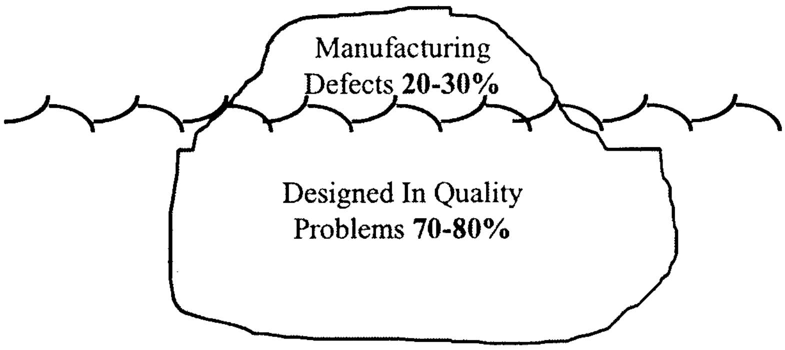
LLL 5

During the Conceptual/Preliminary Design Phase 70% of the cost is implicitly committed for 1% of the cost explicitly incurred. It is here that the Engine Configuration, Design Life, Material Selection and Performance requirements are set. Consequently Conceptual/Preliminary Design represents the best opportunity for cost reduction.

- Cost reduction at low investment
- Ability to change all components
- Engine architecture is flexible
- No hardware changes and no field replacements

An impediment to this process has been the availability of a cost model that would provide the required accuracy with minimal design definition at the Conceptual/Preliminary Design phase and provides zooming capability to the higher fidelity required at Detail Design.

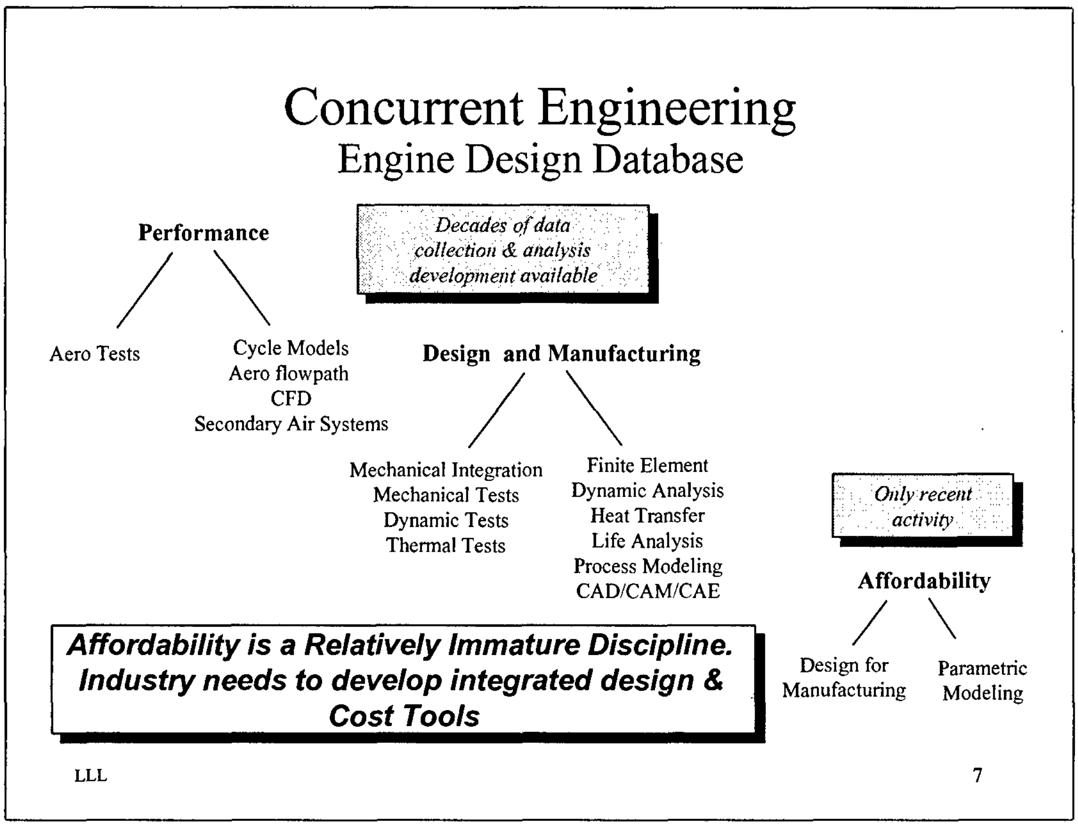
Most Quality Problems Are Designed In



Engineering has the greatest opportunity to improve product quality.

LLL 6

Most quality problems are designed into parts that comprise the system. The place to remedy this is during the design process using Robust Design techniques. This represents the fundamental difference between Cost Reduction, which is predominantly a manufacturing activity, and Design-To-Cost which involves both design and manufacturing. Unfortunately the drive towards higher technology designs has meant that Design-To-Cost principals have not been rigorously applied to all designs.



Cost modeling is an evolving technology. Over the last 50 years engine performance modeling, design and analysis tools such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) and manufacturing techniques such as Computer Numerical Control (CNC) machining have evolved. There has only been recent activity on the concept of affordability. About ten years ago GEAE started research on knowledge based cost estimating techniques that would have similar fidelity to manual estimates but could be automated and used for all phases of engine development from Conceptual through Preliminary and Detail Design and for proposals. The model had to have a built in zooming capability such that the fidelity of the estimate could be refined as the design evolved without changing the underlying assumptions. With the help of funding from NASA and the USAF this work eventually became the COMPEAT$™ cost model.

Cost Model Objective

Cost Offering Method for Affordable Propulsion Engineering, Acquisition and Test

- Cost estimation method
  - Consistent, Fast, Accurate, Complete
  - Variable Fidelity
  - Self Calibrating
- All program phases
  - Development, Test
  - Manufacturing
  - Operation & Support
- All estimating needs
  - Conceptual & Preliminary
  - Detailed Design & Trade Studies
  - Proposal Cost Estimation & Substantiation

LLL 8

The objective of the cost model development was to develop a cost model that would produce consistent, fast, accurate and complete cost estimates for all phases of an engine development program. These would include engine development, test, manufacturing and operation and support. It should encompass all cost estimating needs for Conceptual, Preliminary and Detailed Design, trade studies and proposal cost estimation and substantiation.

Calibration/Validation

The effort required to ensure that the cost model is Current, Accurate and Complete per the Defense Contractor Audit Agency (DCAA) requirements necessitated minimizing the updates necessary. Thus a self calibrating methodology requiring only minimal updates to the database was a necessity.

Validation in Process:

Defense Contractor Management Command (DCMC) Technical Evaluation

Joint GE Internal Auditing/DCAA Review

Integrated Process Team (IPT) Acceptance for Development Proposals
- Negotiated on JSF Alternate Engine Proposal

Estimating System Documentation
- Interim Advance Agreement & Procedure
- Technical Manuals, Policies & Procedures

Cost Modeling Approaches

- Parametric
  - Cost related to power function of weight and size - $\$=A*WGT^B$
  - Simplistic, part specific
  - Cost based on unrelated parameters
- Bottoms-Up
  - Cost determined operation by operation, based on related parameters
  - Accuracy based on statistically large numbers of parts & processes
  - Data & time intensive
- Comparative
  - Uses closest matched part as basis
  - Rationalizes cost differences based on related parameters
  - Material & material process, machining time based on features
  - Accuracy based on statistically large numbers of parts

Comparative Process provides Bottoms Up Accuracy with Parametric Simplicity

LLL 9

There are three approaches to cost estimation, Parametric, Bottoms-Up and Comparative. Parametric is the most simplistic where cost is related to a power function of some high level parameters such as weight or thrust in the form $\$=A*Weight^B$. It is simplistic, part specific but does not take into account design and technology innovation on individual parts. It has the advantage that it requires minimal part definition. It has the disadvantage that cost is based on unrelated parameters. Attempts have been made over the years to refine this by, for example, segregating materials into types (Maurer Factor) or parts into types (earlier GEAE model). Commercial cost models typically use the parametric approach. Bottoms-Up is the most complex where cost is determined by manufacturing operation, based on related parameters. It has the advantage of potential accuracy based on a statistically large number of parts and operations assuming the part definition is complete. It has the disadvantage is that it requires a level of detail usually only found at the detail design phase of an engine development program and it is very labor intensive. The Comparative or Analogy method is the middle ground and uses the closest match part as a basis for the estimate. Cost differences between new and model parts are rationalized based on related parameters such as material and processes and the machining time based on features. It has the Bottoms-Up accuracy based on a statistically large number of parts. Consequently the comparative process provides Bottoms-Up accuracy with Parametric simplicity.

Comparative Cost Modeling Approach

- **Automate** current manual comparative cost estimating methods in a Knowledge Based System
- Use **Consistent Methodology** for Engineering Development, Manufacturing, and Operation & Support
- **Correlation's** based on attributes or features that drive cost
- Use **Comparative Best Match** & adjust for differences
- **Integrate** Engineering Development, Acquisition and Operations & Support results into a Life Cycle Cost Model
- Use **Consistent Process** for Conceptual, Preliminary and Detailed Design stages and for Proposal Estimates & Substantiation

LLL 10

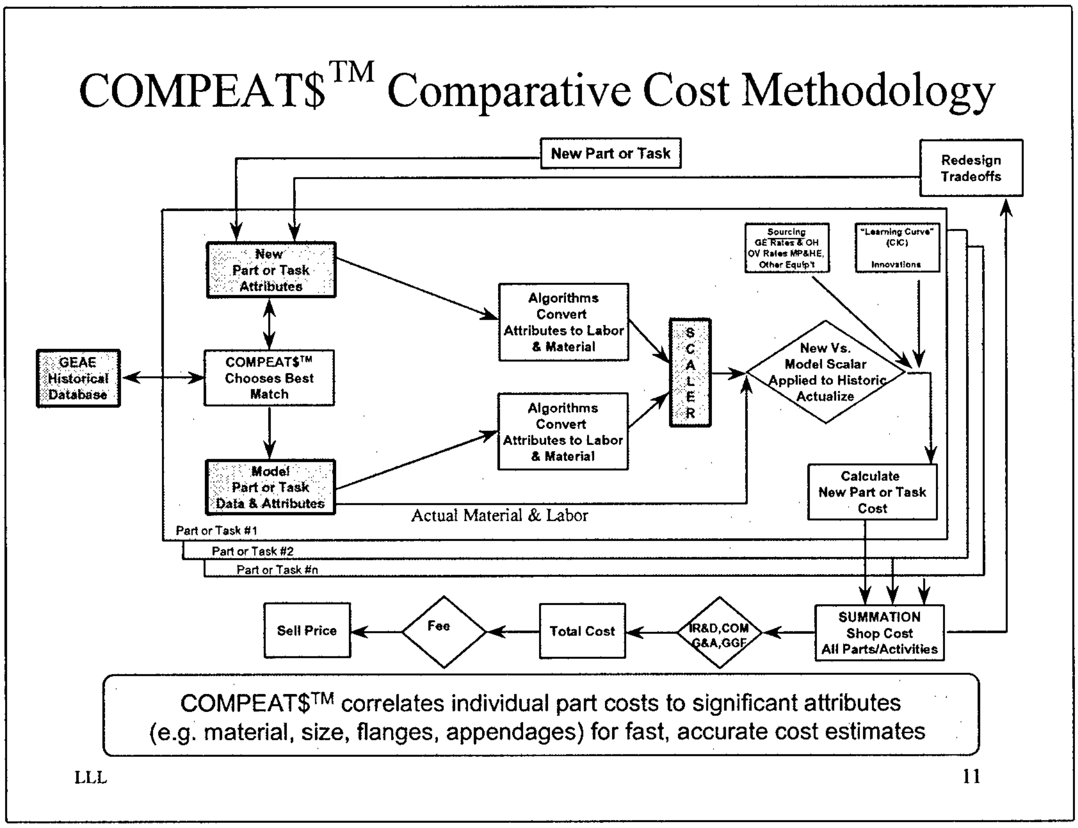
Bottoms-Up cost estimating is usually used only in the detail manufacturing process planning stage of a project. The comparative approach is typically used combined with the expertise of the manufacturing engineer. The approach adopted was to automate the current manual comparative estimating methods and expertise in a Knowledge Based System using consistent methodology for Engineering Development, Manufacturing and Operations and Support. Correlation is based on features that drive cost. The starting point would be to select the comparative best match and adjust for the differences. Integration of Engineering Development, Acquisition and Operations & Support costs would create a Life Cycle Cost model. Picking the best match part (or engineering activity such as engineering, engine test, etc.) selects a default set of attributes for the new part that can be subsequently overwritten as the new the design evolves providing zooming "capability". Thus a consistent process is ensured for both Conceptual, Preliminary and Detailed Design and for Proposal Estimates and Substantiation.

Government/Customer Perspective

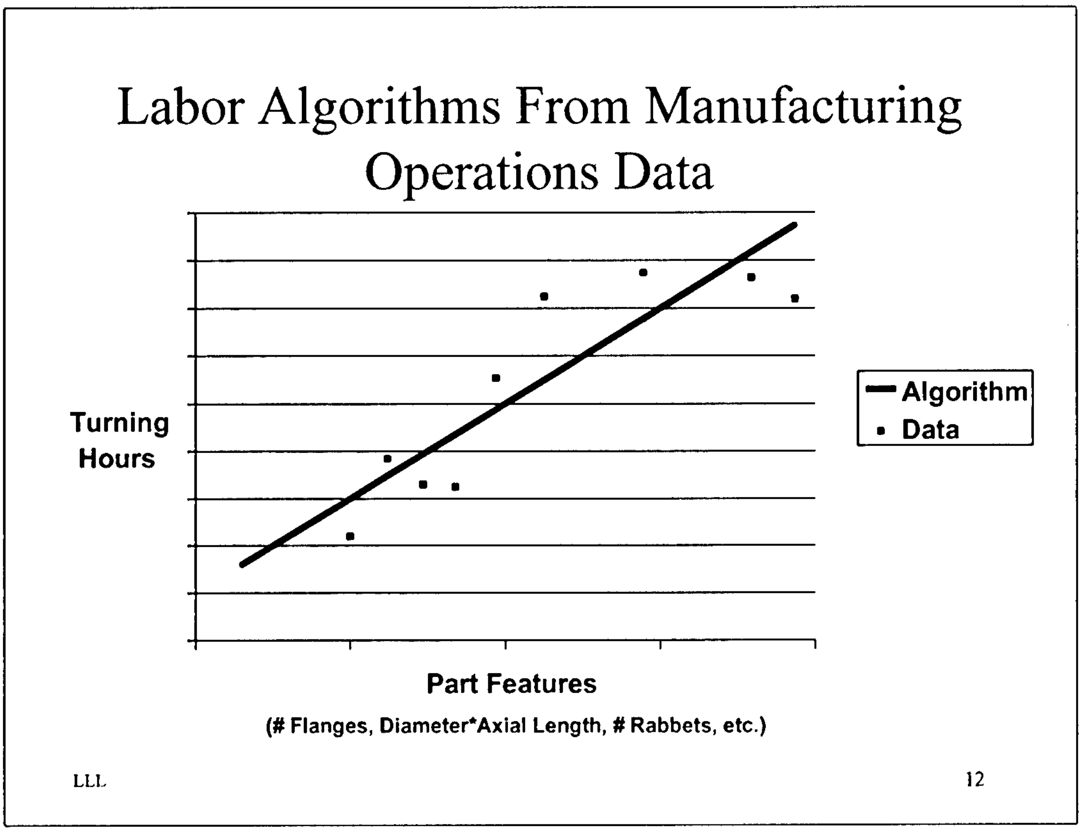
"I am confident that in the not too distant future Parametrics will routinely be a way of reliably predicting future costs when pricing many of our contracts . . . . ."

Ms. Eleanor Spector
Director, Defense Procurement
Parametric Cost Estimating Initiative Workshop -- 10/96

DCAA Quality Conference -- 11/96



This chart illustrates the process for achieving a comparative cost estimate. It will be described for a part to be manufactured but it is applicable to any task. The best match part to be costed is selected from the database of existing parts on the basis of a series of rules. The intent here is to minimize the error of the estimate by minimizing the size of the adjustment. This selection is crucial and, in reality, the best match part may not be the best part for developing an estimate. This is driving GEAE from deterministic to probabilistic cost estimating and the selection of several best match parts as the basis for a statistical assessment of the accuracy of the estimate. The Labor and Material for New and Model parts are then calculated based on the features or attributes of the parts. This is accomplished, not in a rigorous Bottoms-Up approach, but at a higher level using groupings of similar operations of characteristics. These are then used to create a scalar from New to Model that is then applied to the historic actual to create a new part estimate of material $ and labor hours. Component Improvement Curve (CIC, often called a Learning Curve) and Innovation adjustments are then applied to these estimates which are then converted to Shop Cost by the addition of labor rates and other adders. The 150 to 200 major parts that comprise an engine (blades are counted as sets) are then rolled up into an Engine Shop Cost. Other adders to convert Shop Cost to Sell Price are added outside of the COMPEAT$™ cost model. The major benefit of this approach is that the model is self calibrating thus minimizing maintenance. Changes in the algorithms to compare the features on New and Model parts are effectively canceled in the scalar and the material and labor in the Model part is periodically updated.



For each of the part features in a class of parts, manufacturing data was obtained typically from Manufacturing Operation Process sheets. The example shows turning time plotted against part features such as Number of Flanges, Diameter*Axial Length, Number of Rabbets etc. Typically a regression analysis was used to fit a straight line through the data. There is usually significant noise associated with cost data, consequently an R^2 value of 0.7 or greater was deemed acceptable. The benefits of the self calibrating nature of COMPEAT$™ cannot be over-emphasized. Accumulating data for constructing algorithms is very time consuming and labor intensive. This data is also very dynamic and potentially requires frequent update of the adjustment algorithms.

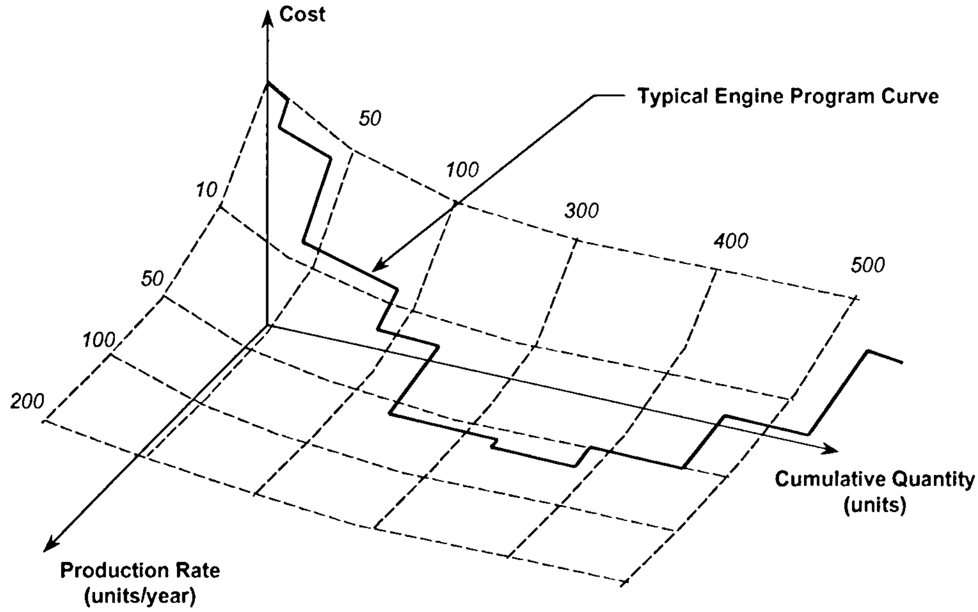
3-D Component Improvement Curve

- Rate of production affects
  - Learning rate
  - Relative cost
- Higher production rates require higher level of automation
  - Lower relative unit cost
  - Lower tooling and other allocated expense per part
  - Lower learning
- Manufacturing Source CIC
  - Application of the CIC slope must be at the assumed rate

13

A key requirement of COMPEAT$™ is the ability to do an estimate at a particular unit number. At GEAE this has historically been the 250th Unit Cost but it is useful to be able to look at different production scenarios. COMPEAT$™ has a 3-Dimensional Component Improvement Curve (CIC). Component Improvement Curves are often called Learning Curves. However CIC includes process improvement in addition to learning. In addition to the usual Cost against Cumulative Quantity of the Number of Units, there is a third dimension of Production Rate in Units per year. This recognizes the effects of high production rates and interrupted production. The COMPEAT$™ parts database has Cumulative Quantity, Production Block, Production Rate, Preload and First and Last Units. Thus adjustments are made on a part by part basis between New and Model. Higher Production Rates require a higher level of automation resulting in a lower relative unit cost, lower tooling and other allocated expense per part and lower learning. Consequently in heavily automated processes the CIC is very shallow at about 95% compared with a more normal 85%. This is because in high production highly automated environments the learning is "built in" up front.

Typical Engine Program CIC



Here we see a typical aircraft engine program learning curve. At the start of production the production rate is low, but this increases as the 250th Unit is approached. At about 450 units the production rate starts to fall again as the program winds down.

Manufacturing Part Families

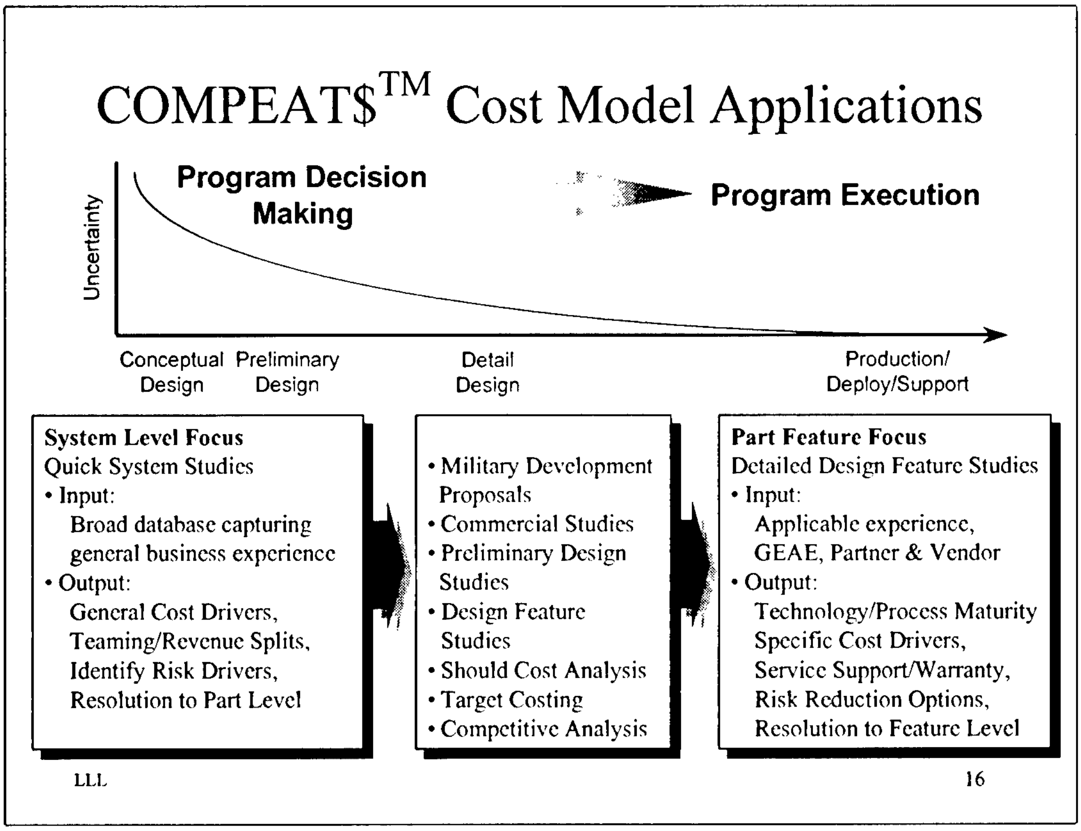
- Casings
- Disks/Spools
- Cooling Plates/Blade Retainers
- Blisks
- Shrouds
- Shroud/Nozzle Supports
- Shafts
- Compressor Blades
- Fan/Compressor Vanes
- HPT/LPT Turbine Blades
- HPT/LPT Turbine Vanes
- Rotating Seals
- Frames
- Combustion Liners
- Bypass/Fan/Exhaust Ducts
- Vent Tubes
- Inlet/Exhaust Centerbody

- Sumps & Bearing Supports
- Compressor VG Actuation
- Bearings
- Static Seals
- Control & Accessories:
  - Gearbox/Drives
  - Fuel System
  - Control System
  - Lube System
  - Ignition System
  - Air System
- Engine Mount Ring
- Actuators
- Exhaust Nozzle Actuation System
- Exhaust Nozzle Flaps & Seals
- Augmentor Liners
- Augmentor Mixer/Flame Holder
- Assembly Inspection & Test

A Large Number of Parts Improves Overall Accuracy

MWB 15

There are 34 COMPEAT$™ Part Families or Part Classes plus the Sum Engine Module. In the initial implementation of COMPEAT$™ more effort was put into the high value parts. Thus the model for disks that comprise greater than 10% of the cost of an engine is more sophisticated than bearings that comprise less than 1% of an engine cost. An additional consideration was that disks constituted GEAE "Make" parts where material cost and labor hour data was available, whereas bearings are "Buy" parts where material cost only was available. The procurement scenario was a key factor in determining the model methodology. Predominantly "Make" parts have material and labor algorithms, whereas "Buy" parts have material algorithms only. "Make" parts that are purchased have material and labor splits applied to them automatically. Accuracy is dependent on a statistically large number of parts and the error decreases by $1/\sqrt{n}$ where n is the number of major parts in an engine. In this context a set of turbine or compressor blades counts as one part. This assumes that all the parts are equally weighted, which is not the case, so this represents the theoretical minimum. Thus estimate accuracy increases from part to module to engine which is of the order of $\pm$ or 3%.



This chart shows how uncertainty decreases during the design process as data is accumulated. During the Conceptual and Preliminary Design Phases the model use would have a system level focus and be used for Quick System Studies. Input would be a broad database capturing general business experience. Output would be General Cost Drivers, Teaming/Revenue Splits, Identification of Risk Drivers with resolution to the Part Level.

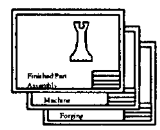
At the Detail Design phase, the model would be used for Military Proposals, Commercial Studies, Preliminary Design Studies, Design Feature Studies, Should Cost Analysis, Target Costing and Competitive Analysis.

During Production/Deploy/Support phases the model would be used for Detailed Design Feature studies. Input would be Applicable Experience from GEAE, Partners and Vendors. Output would be Technology Process Maturity, Specific Cost Drivers, Service Support/Warranty, Risk Reduction Options with Resolution to the Feature Level.

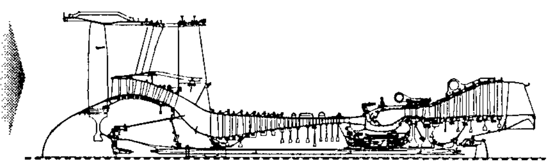
Engine Cost Estimates

Different Depths For Different Purposes

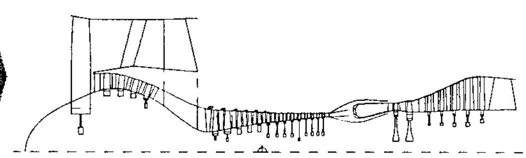
- **<u>The 3 Man-Month Job - Manual</u>**
  - Use ~ 150 Part Drawings
  - Make ~ 6000 Inputs
  - Establishing Engine Baseline



- **<u>The 1 Man-Week Job - Manual</u>**
  - Use 1 Cross Section
  - Start With a 3 Man-Month File
  - Change: Parts List, Airfoil Counts Dimensions, Materials

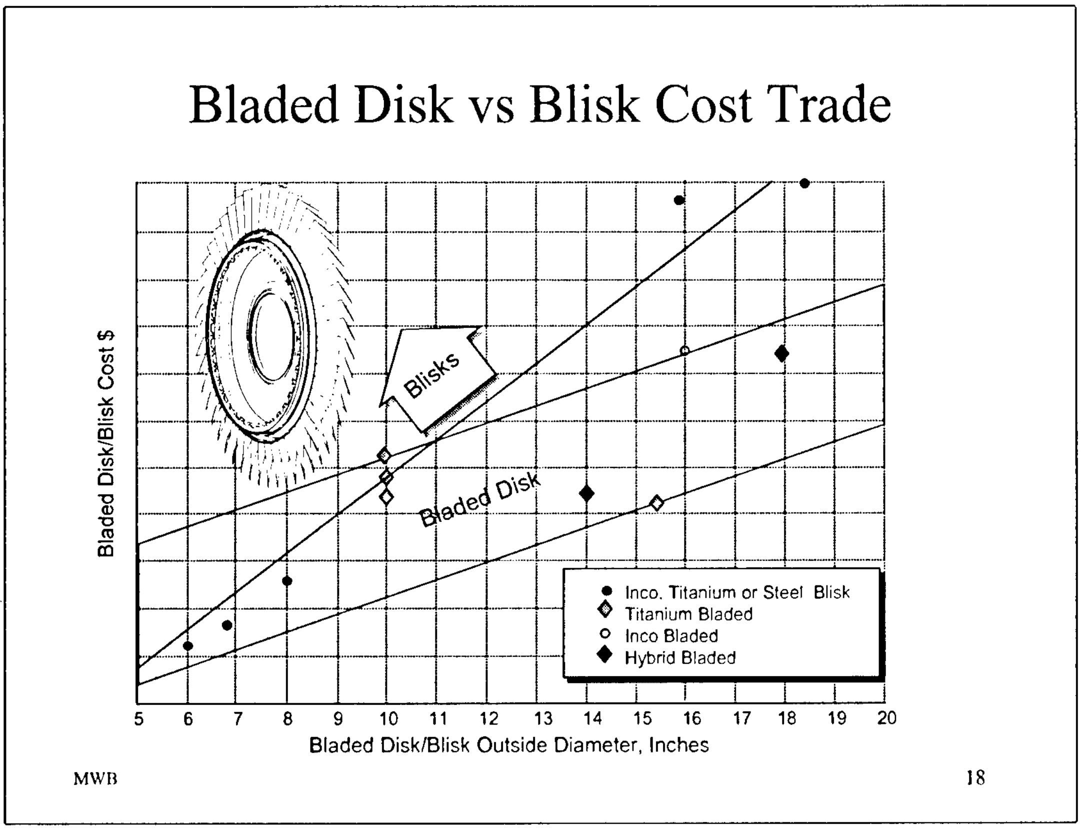


- **<u>The 60-Second Job - Automated</u>**
  - Same As 1-Week But Simple Geometry Overlay
  - Make ~ 600 Actual, ~1500 Inferred, ~3900 Default Inputs,



MWB 17

The objective of developing the COMPEAT$™ cost model was to provide a multiple fidelity analysis tool that could be used for all phases of an engine development program. Historically parametric cost estimating was used during the Conceptual Design phase, Comparative cost estimating during the initial Detailed Design phase, and Bottoms-Up during process planning when the detailed drawings are complete. The disconnects between the different techniques tended to invalidate the original program assumptions and cost trades. Using the same tool with varying levels of fidelity will facilitate a seamless transition from phase to phase. During process planning all the part features can be taken from drawings. At the Detail Design level dimensions can be scaled from a 2-D cross section. At the Concept/Preliminary Design level there would be a simplified geometric overlay. As we move from simplified 2-D cross sections to 3-D solid geometry created at the Concept phase, the fidelity of the one week job will be achieved with the 60-second job, since features will be read directly from the CAD system making the need to infer features unnecessary.



A typical cost trade would be bladed disks versus blisks.

The chart above shows the variation in the cost of single stage bladed disks and blisks with outside diameter. This shows that in small sizes, blisks are less expensive than bladed disks. This is because the cost of removing material from the airfoil section of the blisk (both material and machining) is less than machining the disk and blade attachment dovetails. Above this diameter, since material volume and hence weight increases with the square of diameter, the cost of the material removed make the blisk cost greater than the bladed disk.

Hence the blisk decision on larger sizes would probably be driven by structural considerations. Reducing the number of stages would increase the radius ratio of the compressor annulus, thus reducing the area available for dovetails in the disk with a potential impact on life. This would drive the decision to go to a blisk or add an extra stage. Wide chord airfoils may need to be hollow to further reduce weight but at increased cost since the hollow airfoils would require fabrication and welding to the hub.

Tandem or multiple stages further complicate the problem. On a tandem disk turning and milling is simpler since there are two mating faces not four. Machining the airfoils is simpler since two sets can be made on the same setup. However material costs may be higher since a forging that is twice the weight will generally cost more than two smaller single forgings.

First Order Manufacturing Constraints & Requirements

Design To Cost and Manufacturing Process Considerations

Session 2

Design To Cost

- *Life Cycle Cost & Affordability* — *Mr. Loren L. Long*
- *Requirements verses Constraints* — *Mr. Michael W. Bailey*
- *Cost as a Design Parameter*
- *Concurrent Engineering*
- *Cost Modeling Approaches*
- *Cost Modeling Applied to Proposals*

☐ *Manufacturing Process Considerations*

- *Process Maturity & Capability* — *Mr. Jeffery G. Herbert*
- *Effects of Process & Maturity & Capability*
- *Effect of Geometric Constraints*
- *Effect of Tolerances*

MWB 19

We will now discuss process maturity and capability and their effects. A key element in reducing the engine development cycle is developing key technologies prior to program launch. Included in this would be new processes and process capability. The intent would be to establish and integrate a producibility assessment methodology within Preliminary/Conceptual Design, Detail Design and Engine Systems. Thus product launch would be the execution of the design using established maturity and capability. This would entail an understanding of the effects of geometric constraints and tolerances as they apply to the design.

Process Maturity And Capability

- Product Maturity includes
  - Manufacturing Experience
  - Technology/Design Maturity
  - Repair Experience
- Product Commonality includes
  - Other Systems
  - Other Subsystems
  - Other Parts & Components

Product Maturity + Product Commonality = ***Process Maturity***

- Process Capability includes
  - Optimizing Design Envelope/Space
  - Configuration and Tolerance
  - Material Maturity

Process Maturity versus Process Capability = ***Risk***

JGH 20

Product Maturity includes Manufacturing Experience, Technology/Design Maturity and Repair experience. Product Commonality includes commonality with other Systems, Subsystems, Components and Parts. Hence

Product Maturity + Product Commonality = Process Maturity

In practical terms this means that the closer the part is to one that already exists relative to both material, features and the processes to make it, the more learning is already built into that part. A concept that has historically been used to describe this is % Common vs % Unique. The GEAE Component Improvement Curve (CIC) model has the CIC curve flattening out after a number of units after which no significant learning occurs. The point where this occurs is dependent on the commonality with an existing part and it happens at a lower number of engines with a derivative engine than with a new engine.

Process Capability includes optimizing the Design Envelope or Space, assessing the impact of Configuration and Tolerances and Material Maturity. Hence

Process Maturity verses Process Capability = Risk

Here the intent is to optimize the overall design such that existing process capability can be used to manufacture the parts as designed. For example the drive towards wide chord airfoils to improve compressor efficiency increases the manufacturing risk because the process, although capable of producing the desired airfoil geometry, is not mature enough to do so at an economical scrap rate therefore increasing the risk.

Manufacturing Process Considerations

- Hot Forge Process
  - Die shape
  - Material
  - Material temperature
- Cold Roll Process
  - Die shape
  - Material
  - Number of passes required for final shape
- Raw Castings
  - Features/complexity
  - Process repeatability
- Near-net Shape
  - Machining and shop cost savings
  - Stock needed for 100% clean-up on all machined surfaces

JGH 21

One of the first items to consider in the design of an airfoil blade or vane is the type of manufacturing process that will be used and the process capability of the equipment. If the blade is to be manufactured by a hot forge process, then the temperature of the slug and the rate of cooling becomes a factor in the quality of the part, as well as the size and curvature of the forge die and the type of material from which the blade will be manufactured.

In the cold roll process, temperature is not a factor, however, the number of rolls needed to work the material into its final shape can be a critical factor in the quality of the final part. The amount of work needed to thin and form the material is important when determining how many passes are needed from starting to final shape. In some cases, if too much work is needed on a final pass, the material may tear or it may be impossible to do enough work on the material to get it into a correct final shape.

In the case where an initial casting is used and final machining is done to produce the final part, the main source of variability comes from the quality and repeatability of the incoming material, and in some cases from multiple vendors.

Finally, in order to minimize shop costs, a 'near-net' shape definition of the raw casting is usually released. This reduces the number of hours needed to bring the raw casting into its final machined condition. The major problem is to define an optimal shape that minimizes stock on the final part shape, yet includes enough material so that 100% clean up is achieved after all machining operations.

Blade Geometric Characteristics

- Mid-Span Shroud
- Airfoil Root Fillet
- Platform
- Airfoil Shape
  - Warp
  - Contour
  - Bow
  - Thickness
  - 3-D aero shape

JGH 22

Among some of the geometric characteristics that can effect the quality and the producability of the blade is a mid-span shroud on an airfoil. This adds additional complexity in the forge process to position the shroud in the correct orientation with the added factor of a fillet being machined around the shroud as it intersects with the airfoil.

In many cases, there is not the luxury of a complete airfoil root fillet which fits completely around the blade platform. This brings in the complexity of producing a fillet that may need to be truncated or hand-benched to fit on the platform at a particular point. Critical points are around the leading edge and the trailing edge of the airfoil.

The blade platform can pose problems in the manufacturing process because it must be located in the correct position and orientation to the airfoil to ensure the designed performance is achieved in the engine. If this orientation is off by just a fraction of an inch, the airfoil will not be in its correct position and may not produce the desired pressure rise at a given stage.

Among the most critical features of the blade is the actual airfoil itself. Great care is taken to ensure that the contour of the airfoil, the warp and bow of a section relative to another section, and the airfoil thickness fall into the required tolerance band. More recently with the introduction of a truly 3-D aero shape along the leading edge, this adds an additional level of complexity relative to both manufacture and inspection of the blade geometry, and has led to a significantly increased scrap rate.

Geometric Tolerances

- Varies with size and function of part
- Quality vs. Cost tradeoff

  (e.g. a tighter tolerance may require a different, more expensive process to manufacture the part)
- Need to look at assembled conditions

  (look at parts with the largest percentage contribution to stack-up)
- Need to look at process standard deviations (σ value)
- Moving from USL/LSL approach to process tolerancing

	Traditional Tolerance	Controlled Process Tol.	Absolute Limit	Min % Confidence Control Process
e.g.	$.050 \pm 0.05$	.055	.060	95
		.045	.045	

JGH 23

Traditionally, many tolerances were determined by looking at a similar part drawing and using the same tolerances on the current part being designed. This method, however, can result in previous mistakes being passed on to new designs. A tolerance which is too loose can result in gaps or steps in mating parts or parts which simply cannot be assembled in extreme cases. A tolerance which is too tight may require a more expensive process to hold to the unnecessarily tight tolerance for the process (e.g. a special machine with high precision may be required, but this will also add to the cost of the part).

A statistical approach looks at the function of the part in the assembly, the mean and standard deviation in the machined part and how this can affect tolerance stack-up error in the assembly. Using these tools, it is clear to see that opening tolerances, as has been the case in the past when scrap or re-work is a problem, does not necessary solve the problem and can make it worse downstream.

The method of process tolerancing gets away from the 'goal post' or upper specification limit/lower specification limit approach and moves to the approach where the process should be centered about the nominal condition, and a certain controlled process tolerance is specified in which 95% of the measured dimensions must fall into. This gives a better reliability number for each of the manufacturing processes.

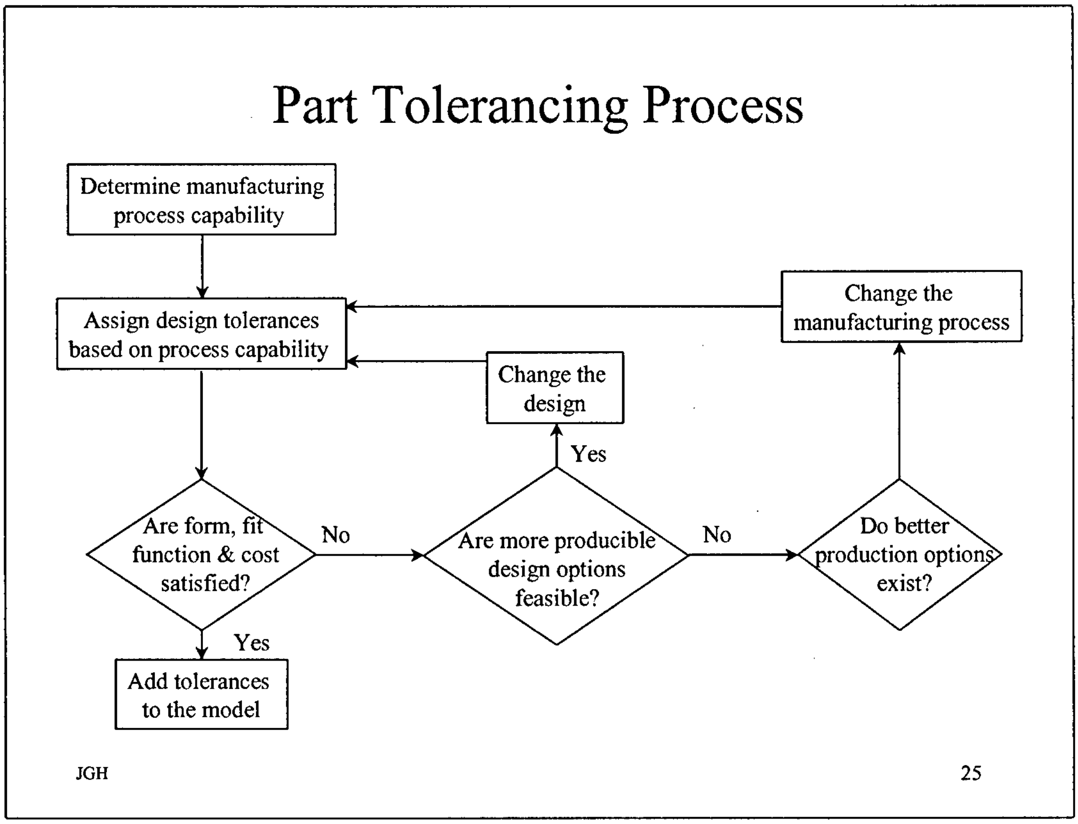
Manufacturing Process Issues

- Cost
- Production requirements
  - Number of parts required and when (scheduling issues)
  - Number of critical features on the part (CTQ's)
- Process capability
  - Tolerance capability of the machines
  - Tolerance measurability of inspection equipment

JGH 24

The cost of the design is always one of the most important manufacturing concerns. Whereas the design engineer is concerned about the performance and the life of the part in question, manufacturing focuses on the cost of the raw material, the shop floor space required for the process flow and machine capacity to manufacture the part, and the complexity of the features on the part and the potential for losses due to scrap, re-work and inventory.

When laying out the manufacturing process for a given part, the process capability must also be taken into consideration. If the desired tolerance is too tight for the capability of the machine, then a different, more expensive machine may be required to hold the tolerance on the feature. The other major consideration is the repeatability and reliability of the inspection equipment. The gages used to inspect the measured features must be able to measure to the desired accuracy and also give the same answer in a reliable fashion.



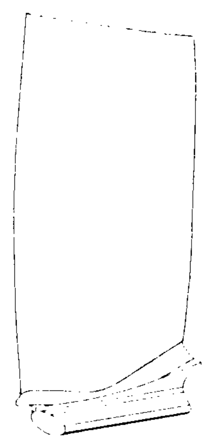
This process map shows the ideal process where tolerances are assigned to a part feature based on the form, fit and function of the part in the overall assembly, typically, tolerances get assigned when the design engineer looks at a drawing of a similar part and assigns tolerances based on a previous design, instead of looking at the part and it's function in the sub-assembly.

Also, a consideration that should be addressed is the process that is going to be used to manufacture the part. Can this type of process support the tolerances which have been placed on the features? If not, then either the manufacturing process must be changed, or the tolerances adjusted, or the design changed.

The current COMPEAT$™ cost model does not use process models for machining, although there are process models for casting, forging and coating. The machining process is implicit in the algorithms and reflects best practices. For example ceramic tooling and its associated metal removal rates are assumed for all materials except titanium. A future development of COMPEAT$™ would include process capability as a variable.

Compressor Blade CTQ's

- Warp
- Bow
- Contour
- Thickness
- Dovetail Pressure Plane



JGH

26

When looking at the manufacturing process from compressor blades, especially large, unshrouded blades, the items which are Critical To Quality (CTQ) are items to pay close attention to when mapping out the process. The characteristics are the few critical factors which effect the overall performance of the part in the engine. If these are ignored, or are not tightly controlled, then the part will not perform to the design specifications.

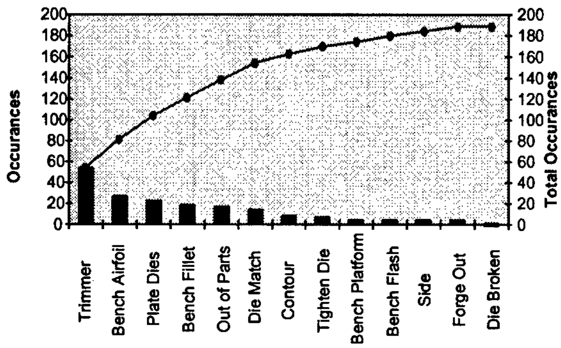
In the case of a compressor blade, the CTQ's are typically the warp, bow, contour and thickness of the airfoil sections and the relationships between them.

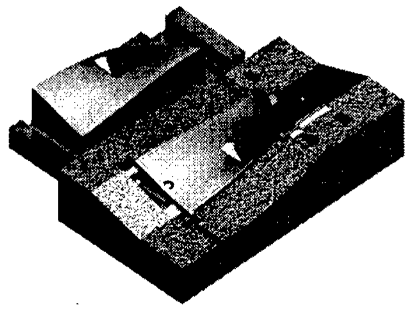
Also, the dovetail pressure plane is important to ensure that the blade is properly seated in the disk post and is correctly oriented when assembled in the disk stage sub-assembly.

Another issue which is emerging as a result of the DFSS initiative is the relationship of part tolerances to system performance based on the CTQ flowdown. This will be discussed more fully in Session 3.

Manufacturing Process Issues

Causes of Interuption for the Final
Forge Run-12000+ Pieces in 1997





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As in any data-driven process, finding the root cause of a problem is always the most important item. As in this example, parts were typically late in arriving to the rotor assembly area for build up into the rotor stage sub-assembly. In the past, many fingers were pointed at individuals who were at the end of the process as being delinquent. In the Design For Six Sigma data-driven world, the most common comment is ‘show me the data’. In this case the data points to one of the major root causes for interruption in the blade forge process, and thus the first place to begin to improve the process. The data points to the forge die trimmer as being the largest cause of problems with the hot forging process, and thus initial process improvements projects should be focused on improving the trimmer.

Summary

- *Cost is now significant as a Design Parameter*
- *The Performance Floor & Affordability Ceiling define the Design Space*
- *Conceptual/Preliminary Design provides the best opportunity for cost reduction*
- *Affordability is a relatively immature discipline*
- *Comparative approach offers the best methodology for cost estimate automation*
- *The same cost model should be applicable to all phases of the program*
- *Process Maturity & Capability define Risk*
- *Matching the manufacturing process to the part is critical to achieving the desired quality*
- *Part tolerancing must be matched to the part function in the system*
- *DFSS methodologies are used to identify process deficiencies*

MWB 28

Summary

- Cost is now significant as a Design Parameter
- The Performance Floor & Affordability Ceiling define the Design Space.
- Conceptual/Preliminary Design provides the best opportunity for cost reduction.
- Affordability is a relatively immature discipline.
- Comparative approach offers the best methodology for cost estimate automation.
- The same cost model should be applicable to all phases of the program.
- Process Maturity & Capability define Risk.
- Matching the manufacturing process to the part is critical to achieving the desired quality.
- Part tolerancing must be matched to the part function in the system.
- DFSS methodologies are used to identify process deficiencies.

First Order Manufacturing Constraints & Requirements
Common Geometry and Multidisciplinary Design & Optimization

Session 3

☐ *Concept of Common Geometry* — *Michael W. Bailey*
- *Geometry as a Design Integrator*
- *CAD Integration with Analysis*
- *CAD Integration with Manufacturing*

☐ *Multidisciplinary Design & Optimization* — *Jon M. Vishnauski*
- *The Move towards Robust Simulation*
- *Robust Design Techniques as applied to Engine Systems*
- *Relating Part Robust Design to System Robust Design*

MWB 1

In this session we will discuss future developments. A key area is the concept of Common Geometry or Master Model.

There are many definitions of a Master Model. At GEAE the definition is a single geometric representation, ideally 3-D, created at concept using feature based parametric modeling techniques in a linked associative environment. In addition there would be a tight integration of all elements of a product creation, manufacturing and support permitting true concurrency for analysis and manufacturing since updates can be flowed down to the individual activities from the Master Model.

An additional requirement is the management of all types of data or metadata within the Common Geometry environment.

Historically analysis codes were coupled together with input and output files with geometry provided as an output as necessary, probably in the form of an IGES file. The new approach is to have geometry central or Common to all the processes and use geometry as a design integrator. This would facilitate CAD Integration with Analysis and CAD Integration with Manufacturing.

Paper presented at the RTO AVT Lecture Series on "Integrated Multidisciplinary Design of High Pressure Multistage Compression Systems", held in Lyon, France, 14-15 September 1998; Cologne, Germany, 17-18 September 1998; Cleveland, USA, 22-23 September 1998, and published in RTO EN-1.

Design For Six Sigma

DFSS

Design for Producibility Robustness

Matching designs with manufacturing capabilities to achieve products producible to 6σ

<u>**Infrastructure Requirements**</u>:

- *Model-Based Product Definition*
  - *Common Geometry*
- *Engineering/Manufacturing Integration*
- *Process Capability Data*

Design for Reliability Robustness

Matching designs with operating environment to achieve products that perform to 6σ against their requirements

<u>**Infrastructure Requirements**</u>:

- *Model-Based Analysis*
  - *Common Geometry*
- *Robust Simulation*
- *High-Fidelity analysis*

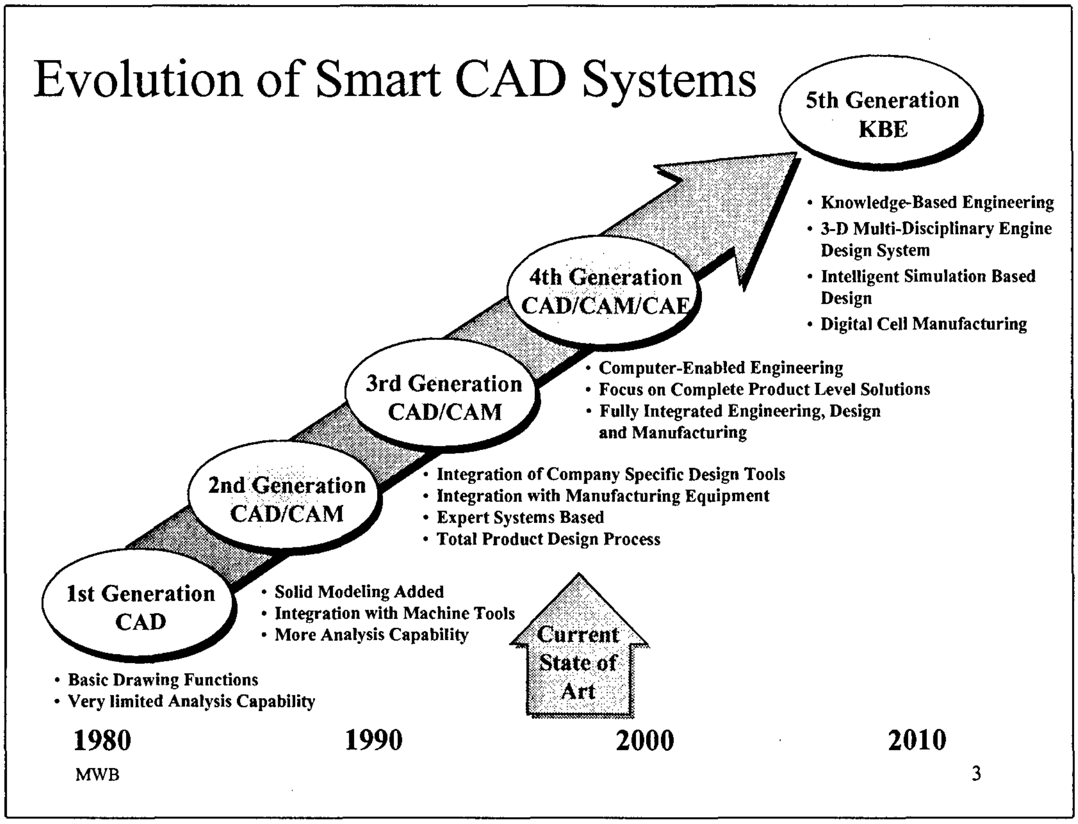
Objective: Six Sigma Performance on Producibility & Reliability CTQ's

MWB 2

The Design For Six Sigma (DFSS) initiative at GE combines two elements: Design for Producibility Robustness; and Design for Reliability Robustness. Design for Producibility Robustness is matching designs with manufacturing capabilities to achieve producible products to Six Sigma. Here the infrastructure requirements are Model Based Product Definition or Common Geometry, Engineering/Manufacturing Integration and Process Capability Data.

Design for Reliability Robustness is matching designs with their operating environment to achieve products that perform to Six Sigma against their requirements. Here the infrastructure requirements are Model Based Analysis or Common Geometry and Robust Simulation which involves High Fidelity Analysis.

The objective here is Six Sigma Performance on Producibility and Reliability CTQ's.



This chart shows the Evolution of Smart CAD systems over time. The First Generation of CAD had basic drawing functionality and very limited analysis capability.

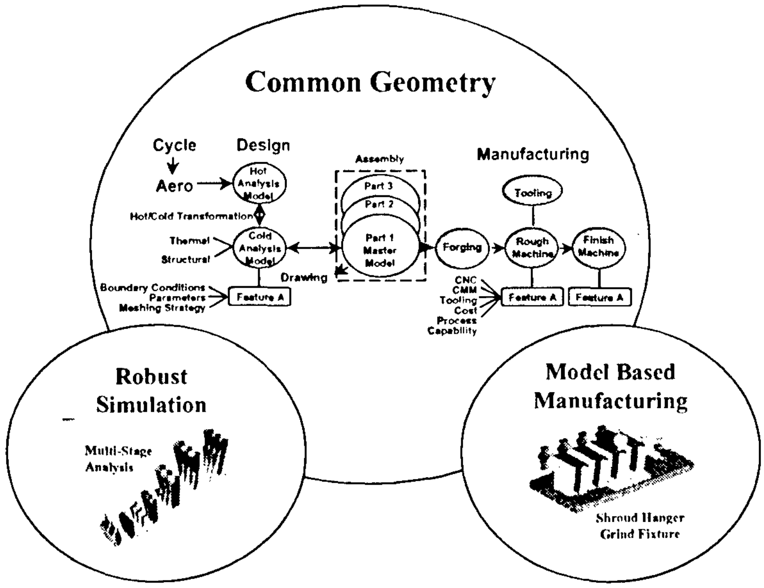
In the Second Generation CAD/CAM solid modeling was added, together with machine tool integration and more analysis capability.

Today we are at the Third generation CAD/CAM where there is integration of company specific design tools, better integration with manufacturing equipment and a move towards building more intelligence into the system to create a total design solution.

The Forth Generation will encompass Computer Aided Engineering and focus on complete product level solutions to provide a fully integrated design and manufacturing environment.

The Fifth Generation is Knowledge Based Engineering and is characterized by the NASA Intelligent Synthesis Environment initiative. It will be a 3-D multidisciplinary engine design system incorporating intelligent simulation based design and digital cell manufacturing.

Common Geometry Approach



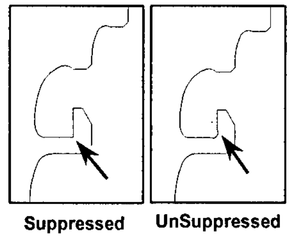
Common Geometry is the foundation for design and manufacturing

MWB 4

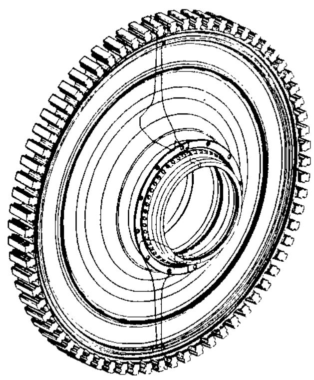
This chart shows the main elements of a Master Model. The thermodynamic cycle is used as input to the aerodynamic analysis model which creates hot gas path geometry. This is converted to hot solid geometry in the Hot Analysis Model. Subsequent conversion to the cold Analysis Model is through the Hot/Cold Transformation. The cold solid geometry airfoils are then combined with the platform and shank or other attachment features to create the Master Model which would comprise of an assembly. The Master Model is related to the Cold Analysis and Manufacturing models through Context models. These will be discussed in more detail in a later chart. The Master Model is feature based but these features have different applications depending on the Context model. Feature A, which may be a bolt hole, has a stress concentration and loads applied to it in an engineering context, but the process, tooling and cost required to make it are in a manufacturing context. Thus the same common geometry provides an infrastructure and a foundation for both Robust Simulation and Model Based Manufacturing.

Finally the Master Model would be linked to the context models in a linked, associative environment using a Product Data Management System.

Feature Construction



- Piecing the model together from features allows the **suppression** of selective features by downstream users
- Failure of the model on a parametric update will be limited to the features
- Traditional 2-D axisymmetric x-section can still be generated
  - It is completely associative to the solid
  - In this case it is an "output" instead of an "input"
  - Parameters can drive the 2-D x-section



Time invested constructing 3-D models facilitates updates as design evolves

MWB 5

Model construction is of paramount importance if productivity gains downstream are to be realized.

Piecing the model together from features allows the **suppression** of selective features by downstream users using context models.

Failure of the model on a parametric update will be limited to the features.

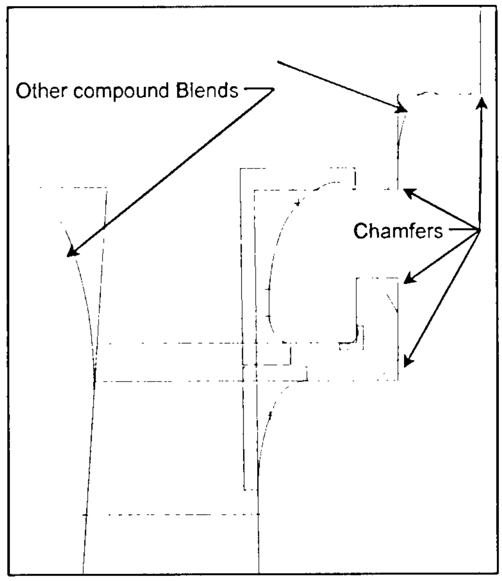
Traditional 2-D axisymetric cross sections can still be generated

- It is completely associative to the solid
- In this case it is an "output" instead of an "input"
- Parameters can drive the 2-D cross section

The time invested constructing 3-D models facilitates updates as the design evolves.

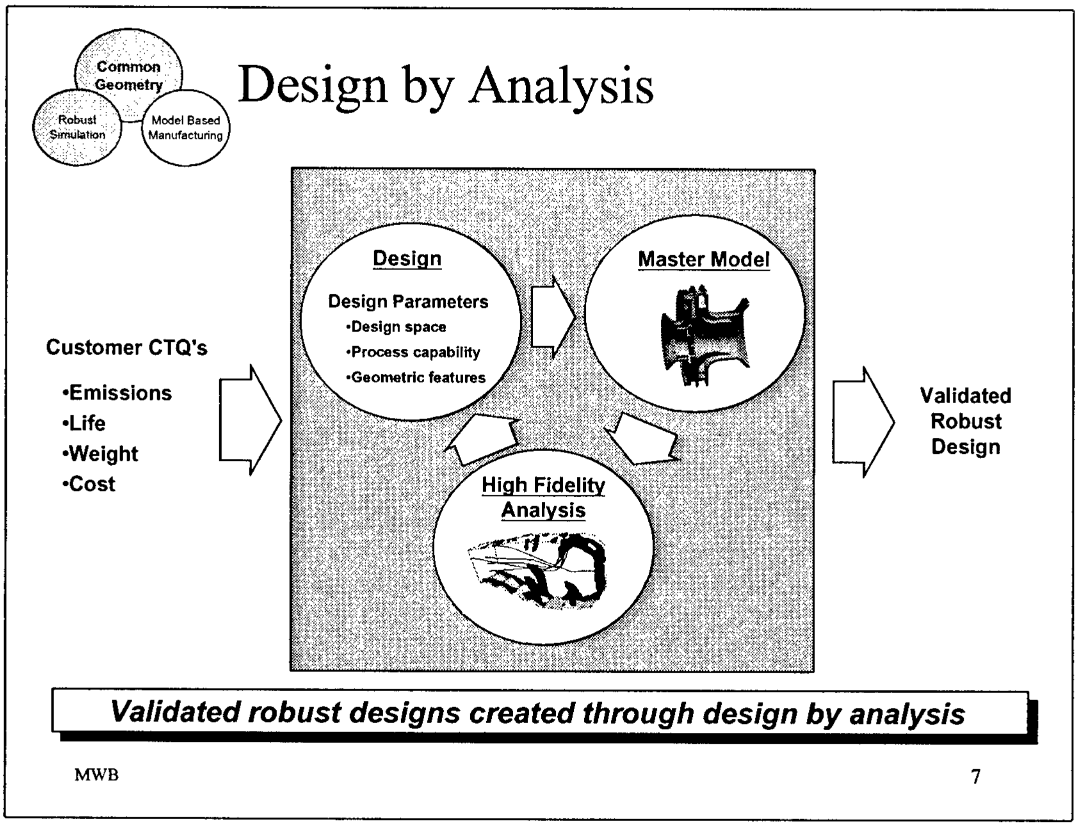
Proposed Modeling Practice

- **Feature Construction**
  - Create Simple Block Shape
    - Sketch → Solid
  - Create Simple Features
    - Sketches → Solids
  - Unite Solids
  - Create Compound Blends
    - Sketches → Solids
    - Extract Trimming Sheets
  - Add Compound Blends
    - Unite Solids
    - Trim with Trimming Sheets
  - Complete Axisymmetric Solid
    - Simple Blends
    - Chamfers
  - Add Non-Axisymmetric Features
    - Sketches → Extrude & Subtract
    - Holes, Slots & etc.
    - Instance

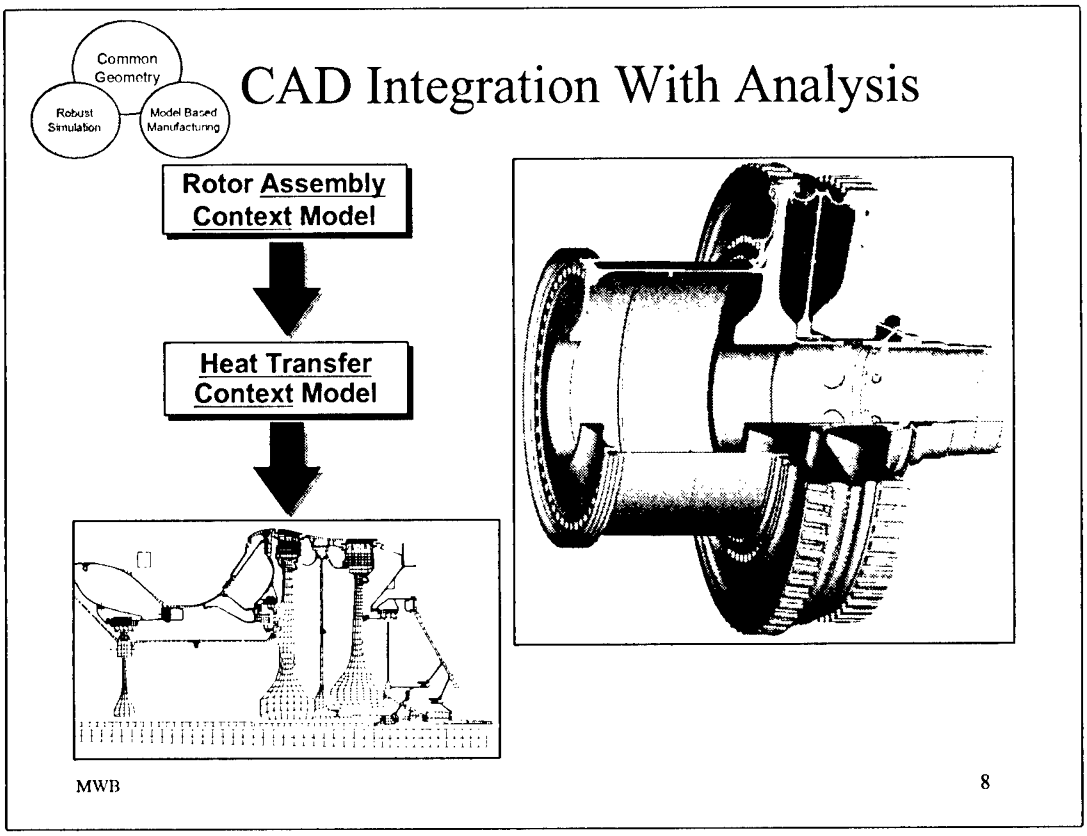


MWB 6

Model construction is comprised of creating a simple block shape base model. To this are attached simple features such as flanges and other appendages. Compound blends are then created and added to the model, together with simple features such as radii and chamfers to complete the axisymetric solid. Non-axisymetric features such as holes and slots are then added. This modeling approach is known within GEAE as "Mr. Potato Head" because of its resemblance to the character in "Toy Story". This feature based approach is consistent with feature based analytical model building and the feature based cost estimating used in COMPEAT$™ and provides feature suppression functionality.



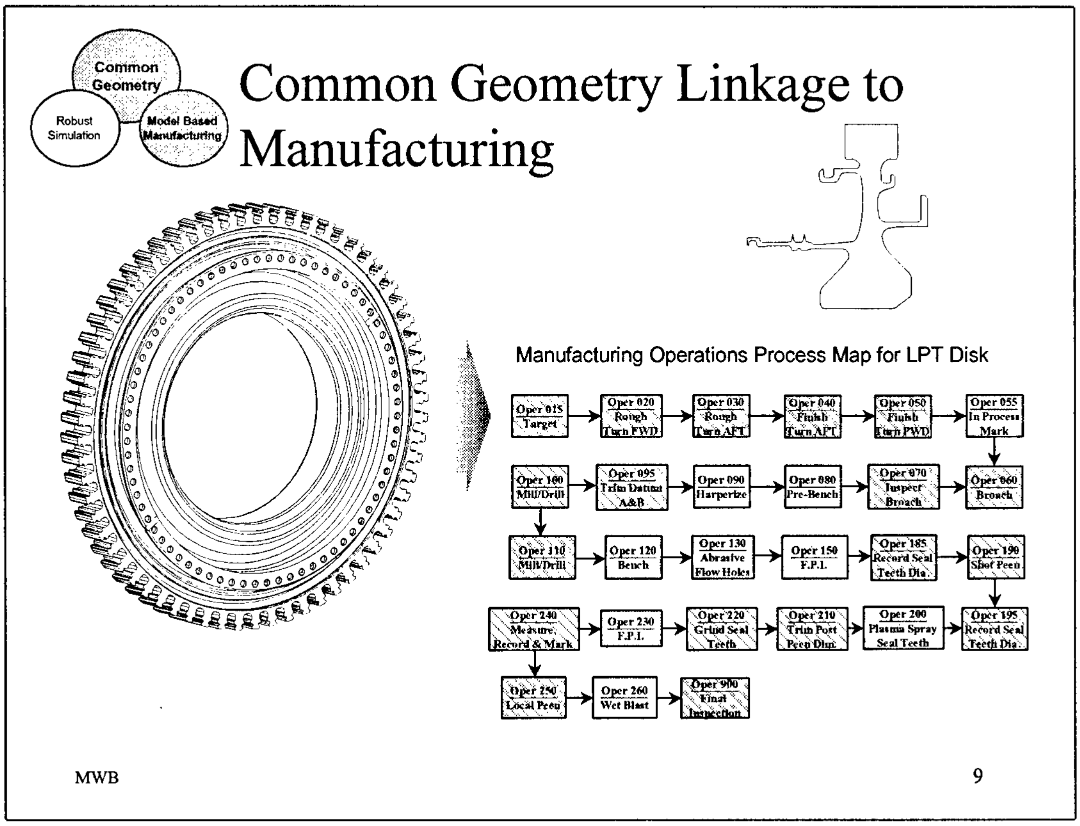
Common Geometry supports the move towards Design by Analysis. Customer CTQ's of Emissions, Life, Weight and Cost would provide input into a design process that would combine Design Parameters such as the Design Space, Process Capability and Geometric Features with the Master Model thus facilitating High Fidelity Analysis. The intent here is to create validated Robust Designs by Analysis thereby minimizing, or in some case eliminating, costly engine and component tests.



A key element in the Integration of CAD with Analysis, or any activity that is geometry dependent, is the creation of Context Models. A Context model uses the concept of CAD Assemblies to create a "view" of geometry. Just as it is conventional CAD practice to combine several parts into assemblies building up into the complete system, it is possible to combine geometry with context information in the form of an assembly. Context in this application means the attachment of information necessary to create a Structural, Thermal or CFD model to geometric entities. The rotor assembly could also be regarded as a context model.

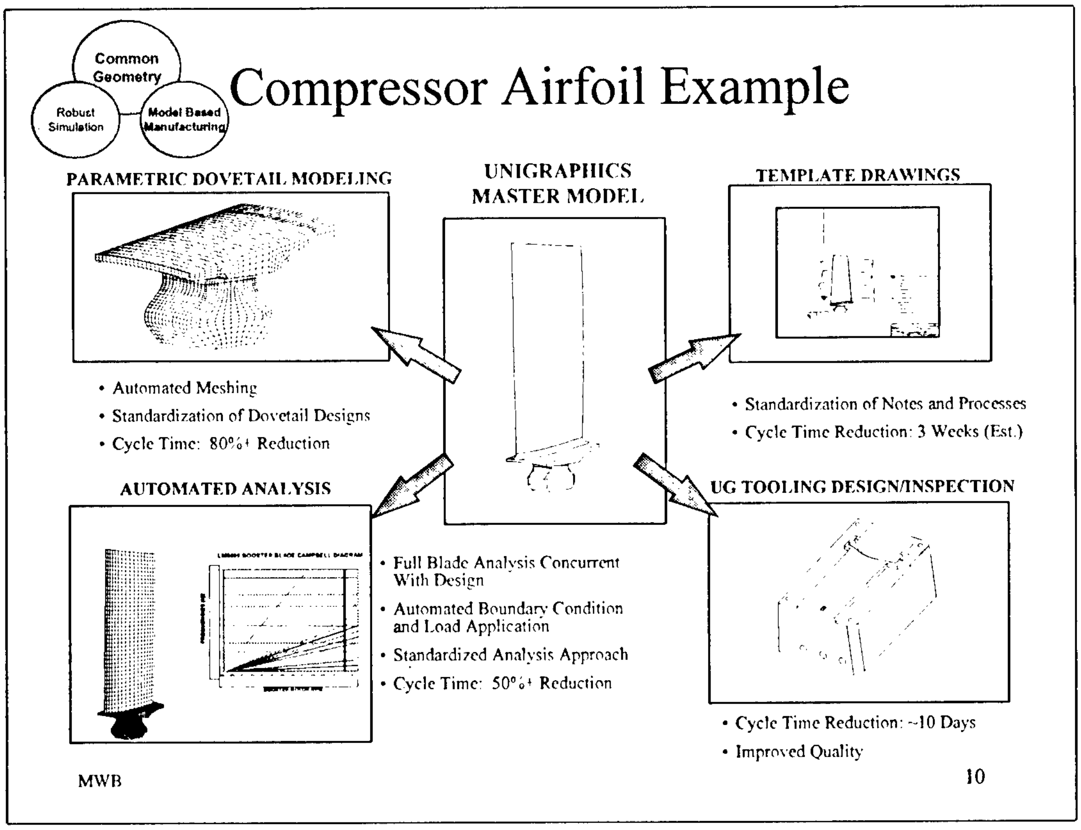
This information could be boundary conditions such as pressures, temperatures, loads and the meshing strategy such as mesh seeds or mesh densities, etc. These attributes are applied to the geometric entities in the CAD package.

This context information or "Tagging" should be robust to parametric or non-topological changes and have some robustness to topological changes. A longer term goal is to apply these "Tags" as the analysis model is built in the meshing software, then export these to the CAD software for storage. Currently they are applied in the CAD software. The CAD assembly context model is imported into the meshing software such as PATRAN, ANSYS or ICEM CFD to create the application model.



During manufacturing there are several in-process models indicated by the shaded operations. Traditionally these are in-process drawings or solid models constructed from these drawings. Computer Numerically Controlled (CNC) machining tapes and tooling are then made from these models. In a Master Model environment, the 3-D solid models would be associatively linked to the Master Model permitting automatic updates when the Master Model is updated. In addition, process planning sheets and other in process information would be automatically generated. In practice the arrows in the process map shown in the slide are reversed since the process models are made by adding material and defeaturing the finished part at each operation until the forging envelope is defined.

Computer Measuring Machine (CMM) inspection programs can also be generated from the process models. This is another key context model use of the linked associative environment. Aircraft engine manufacture involves the machining of complex shapes from high temperature alloys that "move" during the manufacturing process. Thus it is important for process control to inspect the process shapes to know what the dimensions are so adjustments can be made to future machining operations. This offers the possibility of a "real time" feedback loop using the Master Model.



Here is an example of the integration of design, manufacturing and product definition around a Unigraphics solid Master Model.

Parametric Dovetail Modeling

- Automated Modeling
- Standardization of Dovetail Designs
- 80%+ cycle time reduction

Automated Airfoil Structural Analysis

- Full Blade Analysis Concurrent with Design
- Automated Boundary Condition & Load Application
- Automated Frequency Calculations
- 50%+ Cycle Time Reduction

Template Drawings

- Standardization of Notes & Processes
- Cycle Time Reduction 3 Weeks (Estimated)

Tooling Design & Inspection

- Improved Quality Driven by Master Model
- Cycle Time Reduction 10 days

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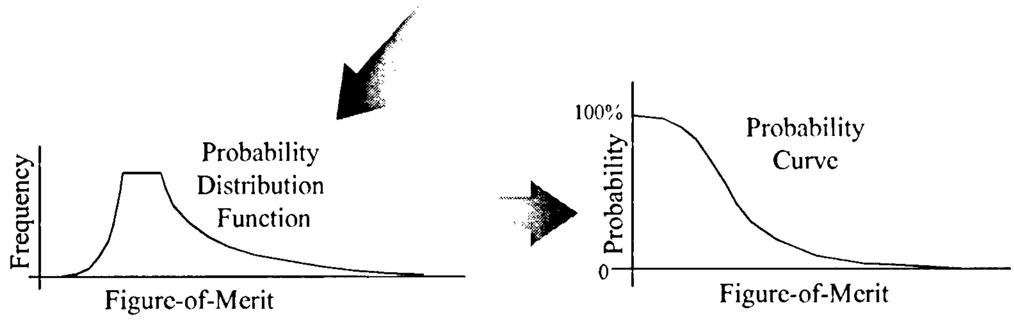
MWB 11

Multidisciplinary Design and Optomization should ideally involve the whole engine system. In the current approach different groups have responsibility for the different aspects of the design. For example, one group may have system responsibility and other groups may have responsibility for aerodynamic design, airfoil structural design and manufacture, rotor structural design and manufacture and static structure design and manufacture. There is a degree of collaboration between these groups but design effort is generally concentrated on the parts not the system often producing a sub-optimal solution at the system level. Work has been done in Conceptual Design to optimize components such as Fan, Compressor, etc. in the context of the overall system. The plan is to extend this to the part level where the intent is to establish a relationship between the CTQ flowdown from the system and the flow up of part resultants to the engine system and ultimately the airplane. This section will discuss the future direction of work on Robust Simulation at GEAE.

The Move Towards Robust Simulation

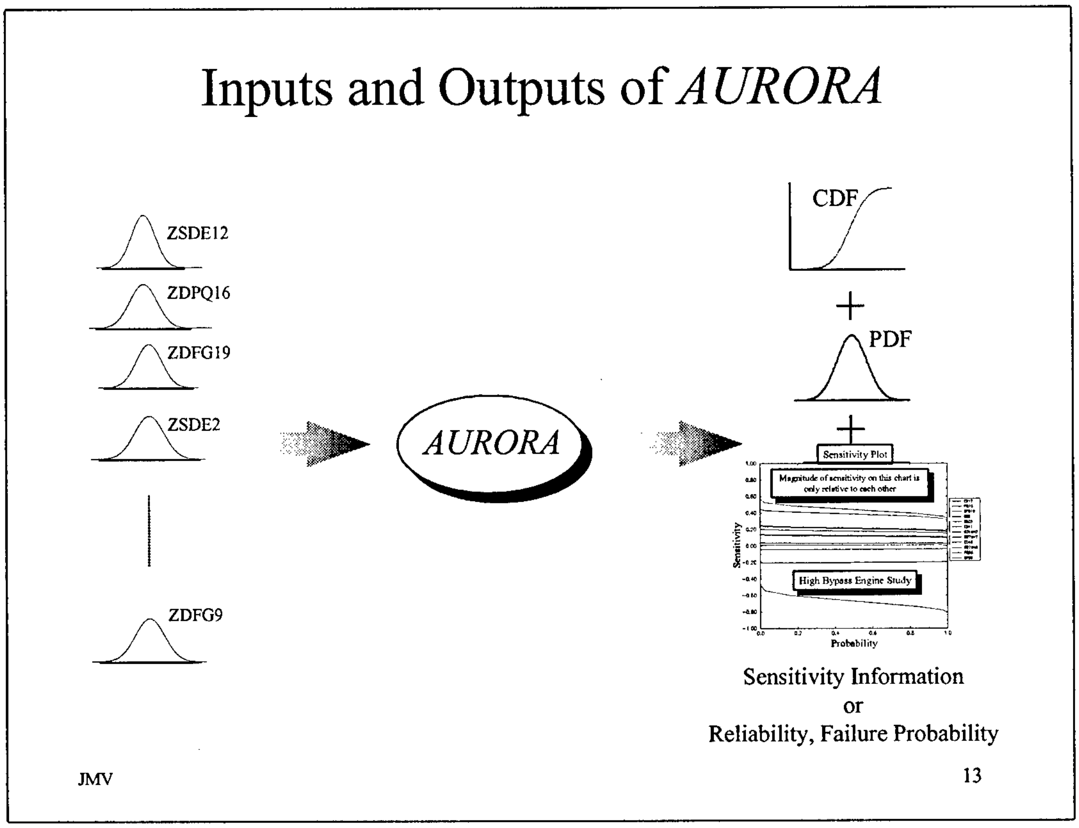
What About Some Probabilistic Data to Complement the Deterministic Solution?

- Need to understand something about the shape and value of the distributions
- Used to measure risk
- How can we create the data?



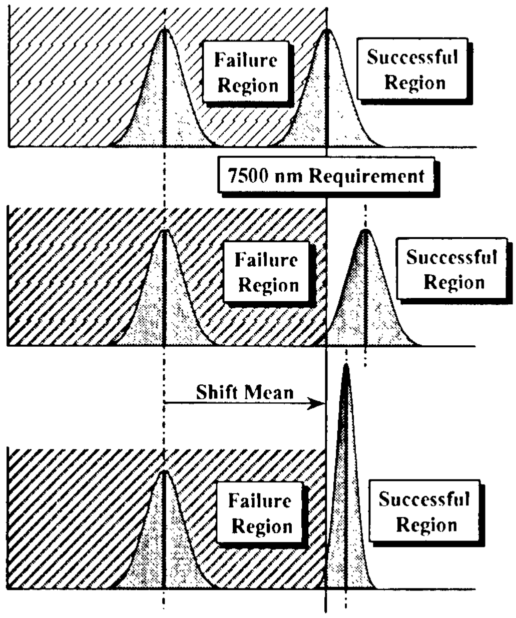
JMV 12

If we could produce some probabilistic data for the resulting system Figure-of-Merit we could gain some insight into the risks involved with the "system". Most analyses are conducted in a deterministic sense, but we know that realistically many inputs into the "system" carry variation. The effects of these random variables would be combined in the overall system and produce a random variation in the resulting system Figure-of-Merit. The Probability Distribution Function (PDF) of the system Figure-of-Merit would show the range of variation and when converted to its Cumulative Distribution Function (CDF) show the probability of occurrence. The shape of this cumulative distribution function is important and gives an indication of the trade in probability and its associated change in system Figure-of-Merit. For example, if we were willing to trade 20% probability (from 100% to 80%) we could determine the change in system Figure-of-Merit and assess the benefits of doing this. Of course, both the risk and benefit have associated costs and the real decision would be the magnitude of the cost ratio. The bottom line is that the probabilistic nature or characteristics of the system Figure-of-Merit is important. It is a function of the characteristics of the random input variables and can provide an insight for risk taking.



Monte Carlo techniques are well known and provide a means for accommodating the random input variables in a system simulation. The process randomly selects values from these distributions and observes the resulting system Figure-of-Merit. Many passes through this process are usually required to describe the frequency of occurrence of the system Figure-of-Merit. Some system simulation run times are long and time consuming, which makes this technique not feasible. Another technique that can produce the needed Probability Distribution Function are the Approximations Used to Rapidly Obtain Reliability Analysis (AURORA) which are a class of fast probabilistic integration techniques. These techniques are approximation techniques to circumvent the need for excessive runs that accommodate the random input variables and produce the needed system Figure-of-Merit Probability Distribution Function. The inputs into the system simulation are the frequency of occurrence characteristics of the important parameters. Outputs consist of both the Probability and Cumulative Distribution Functions for the system Figure-of-Merit, along with sensitivity curves. These sensitivity curves provide information on the importance of each input random variable as a function of probability level. This serves as a starting point for exploring potential changes to the input random variable characteristics and helps drive the system towards a better cost/benefit ratio.

Robust Design Technique



This somewhat satisfies the requirement,... but at 50% Probability

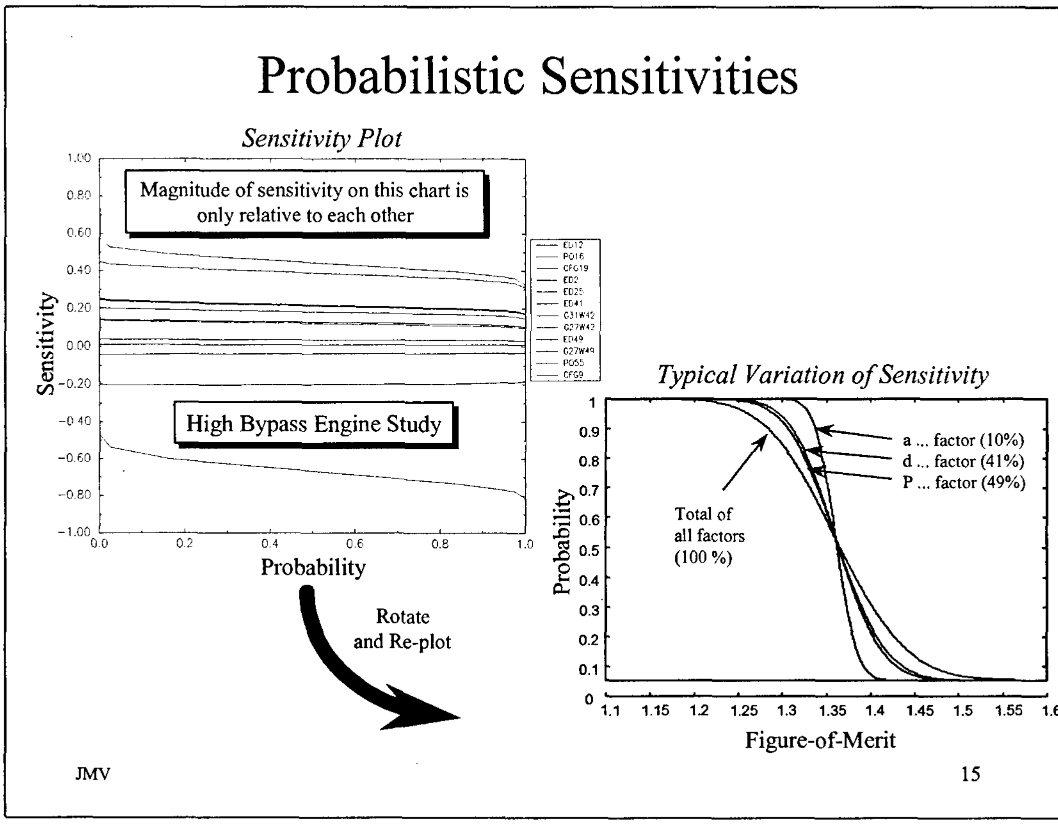
This satisfies the requirement, ... at > 50% Probability, but having to move the mean even more

This combination satisfies the requirement at > 50% Probability and minimizes the mean movement

JMV 14

Typical "Robust Design" techniques would first concentrate on centering the system Figure-of-Merit output distribution on the desired requirement and then focus on reducing the variation to bring the results within specification. For example, the desired range of an aircraft system may be 7500 nautical miles (nm). The system performance may fall somewhat short and requires some changes to move or center the performance. In this case a lower specification limit may be the 7500 nm requirement. There are several ways to achieve this.

The top illustration shows a literal shift in the distribution to place its' mean on the 7500 nm requirement. As the chart indicates, this movement only yields a 50% probability of occurrence, since about half of the distribution falls below the requirement and results in failure. We would like a high probability of occurrence but the probability is related to a cost/benefit ratio. We could shift the distribution to the right such that all occurrences meet or exceed the requirement but the "system" cost may be too high. The middle and bottom illustrations indicate combinations of distribution shifting and shaping to accomplish similar results. The mechanism for changing the system Figure-of-Merit distribution is to change the input random variable distributions or the system requirements and assumptions. The "best" method could be determined by assessing the risk associated with each idea and relating those to the potential benefits. Design changes could be traded off with technology insertion. The probabilistic sensitivities provide a means for making these changes.



A better description of these probabilistic sensitivities is in order. The sensitivities are displayed as a function of probability level and relative to their contribution to the Cumulative Distribution Function of the system Figure-of-Merit. The lines represent the individual random variable inputs into the system simulation and show that some of them change with probability level and others seemingly contribute very little to the output. This information could be utilized to impact certain areas of the probability curve and tailor the shift along with the shape. We should not lose sight of the relatively unimportant random variables. These have associated variation and, like it or not, have a cost associated with them. These variations have historically been controlled by virtue of the way a business operates in the design, manufacture, quality control, maintenance strategy, and service of its products. There is a potential for cost savings when relatively unimportant random variables are observed. The potential for changing their distributions and impacting cost could provide opportunities for high payoffs.

Comparison of Approaches - Pros & Cons

Approach	Engine Models	Relative # Runs	Study Factor Limits	Probabilistic Accuracy	
Deterministic	Base	Base	No	None	*High Risk Answers*
Inner/Outer Array	Same	16x	Yes • # Factors • Interactions	Poor	*Yields Some Information*
Monte Carlo	Same	6400x	No	±5%	*Very Large # Runs*
AURORA	Same	13x	No	High	*# Runs = f(# Random Var.)*

AURORA provides a reasonable method for some applications
... more significant improvements to AURORA can be made

JMV 16

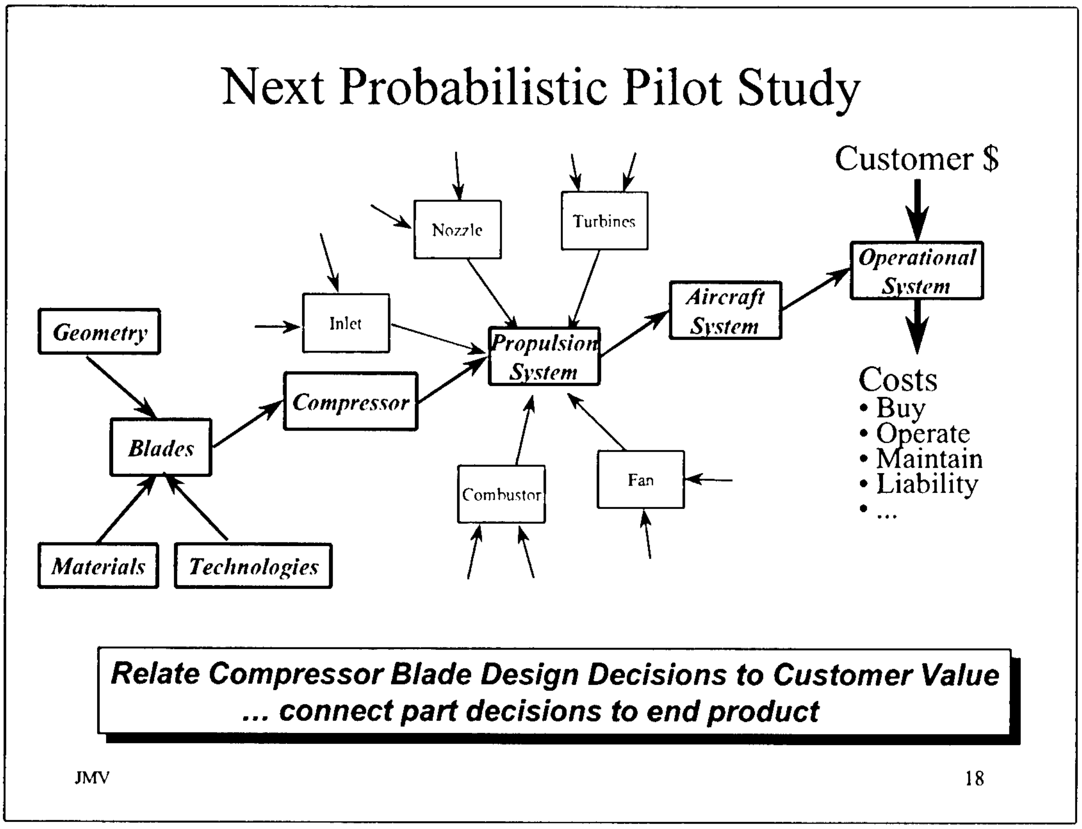
Four approaches are compared and summarized. The base approach is the typical deterministic approach using Design-of-Experiments to gain knowledge over the design space. This approach provides results that are not probabilistic and typically middle-of-the-road. The Inner/Outer Array approach attempts to capture impacts of variation but not a clear understanding of the nature of the distributions. This approach usually is employed to find areas in the design space were the impacts of variation are high and low. The identification of these locations are important to minimize effects of variation if a choice in the design space is possible. The Monte Carlo approach certainly can provide the needed information but using a relatively large number of runs. This may be acceptable if the time constraints are within bounds for the project. The AURORA option provides a reasonable approach for the amount of information that is generated. This approach is a function of the number of input random variables and the desired accuracy of the result. Further improvements in this technique are currently being studied and should greatly reduce the number of runs needed.

Typical Study Issues

- Statistical data for random variables
  - Not readily available
- Simulation Codes
  - Did not always RUN
  - Tedious debugging
  - Too time consuming to run
  - Could not link
  - Discontinuities in results
- Code Integration
  - Required some programming
- D.o.E. generation
  - Limited
- Response Equation generation
  - Data required transformation
  - Difficult to get suitable plots
- Data Analysis
  - Lots of data - Data Management
  - Every discipline needed different
  - Difficult data display/manipulation
- Number of Runs
  - Some techniques required many
  - Length of time
- Procedure dead ends
  - Uncertain analysis process
- Absence of analysis procedures
- Limited knowledgeable people

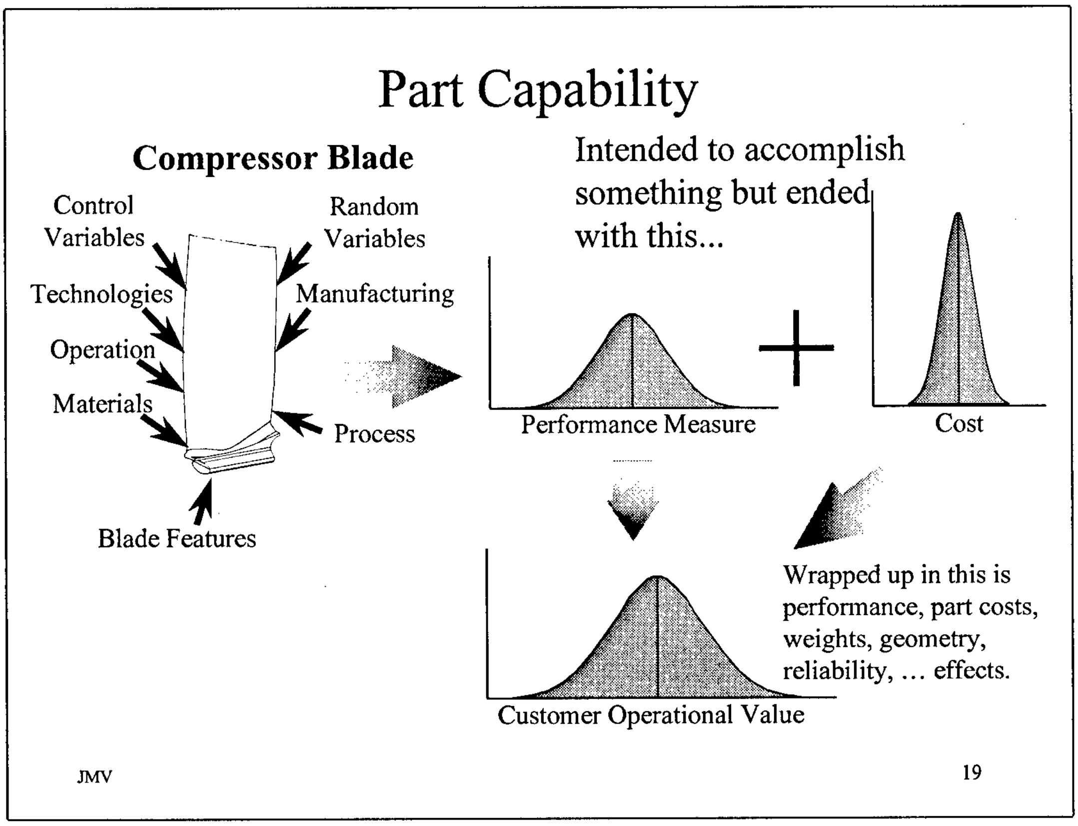
JMV 17

Many issues exist when trying to conduct a systems study of this type. The data that is needed to feed these analyses sometimes does not exist or is also difficult to obtain. Similar approaches to the creation of probabilistic data can be applied to sub-systems and eventually to parts. The study of their variations and what is, or is not, important provides additional synergism in the quest for improved cost/benefits. The above issues are not unique, but indicate the need for an environment that allows for the easy assemblage of simulation codes to quickly represent the process that these studies will follow. These processes should be easily modified and driven by various methods, such as parametric, optimization, Monte Carlo, Robust Design, or fast probabilistic integration techniques.

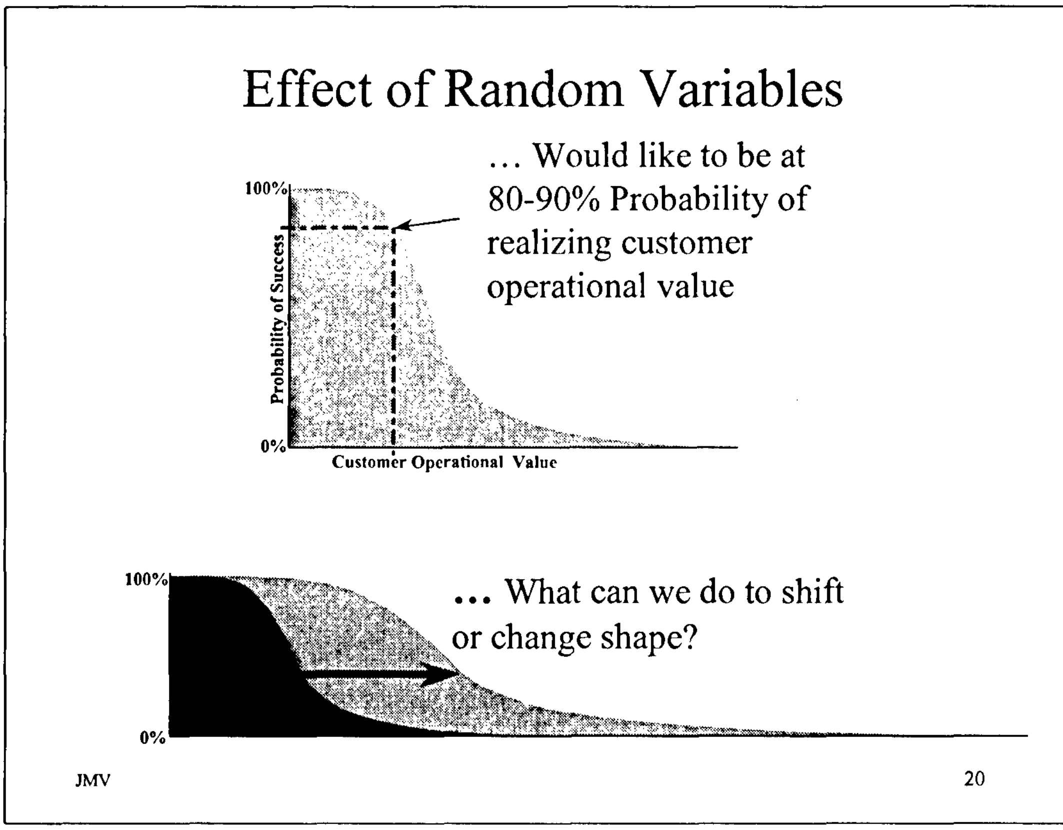


Consider an aircraft system where the subject of study is a particular aspect of the propulsion system. This notion could be applied to many aspects simultaneously but for now it is easier to consider this one complication. Many engineering disciplines are usually involved and are not totally knowledgeable of the "total system". These disciplines require immediate feedback to efficiently make design decisions for the parts that they are responsible for. Every engineering discipline has its source of variation and elements that are important to its successful operation. These variations combine in a way that impacts the variation of the product that they provide to the next discipline in the process. As one can see, this can quickly become complicated and computationally intensive. The probabilistic data that impacts the customer can be used to allow the changes in part design (dimensions, weight, cost, material, technologies, etc.). Risks can be traded off with customer benefits and assessed for high payoff. Many studies can be done in parallel to create the information flow that is needed for quick and meaningful design decisions. An approach is suggested that would explore maximizing the customer value. The concept of excess customer value was documented by Collopy in 1997 (Ref 1). The excess customer value of a commercial aircraft, in simple terms, is the difference between the present value of the profit stream generated by the aircraft and the cost of manufacturing the aircraft and engines. The excess customer value represents the total profit potential of the aircraft, which is divided among the airline, airframe manufacturer and engine manufacturer, through the action of a competitive market.

Ref 1. Collopy, P. D. "Surplus Value in Propulsion System Design Optimization" AIAA Joint Propulsion Conference, July 1997

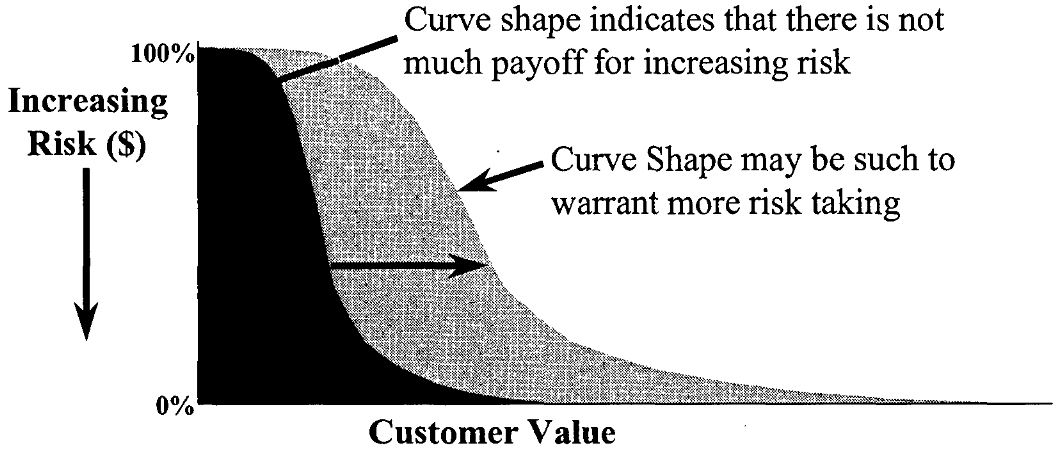


The elements of compressor blade design have some random variation which in turn produces variation in performance, weight, size, cost, etc. These variations become further complicated by their influence upon other components of the propulsion system and ultimately the operational system.



We should keep in mind that the probabilistic information could be used to determine acceptable risks based upon cost/benefit. The above example illustrates the need to determine the shape of the system Figure-of-Merit distribution. Improvements to the cost/benefit ratio are made by controlling or uncontrolling important input random variables or by changing system requirements/assumptions.

Curves Could Look Like These ...



JMV 21

The shape of the customer value distribution is important when studying risk/benefit trade-offs. In one instance, the curve shape indicates a relatively large change in customer value for a small change in risk, and in another instance there appears to be not much of an increase in customer value for increased risk. Increasing risk impacts the cost of business and probably product cost but it could be offset by an associated increase in customer value. Maximizing the difference between these two numbers could provide a way to identify the "best" product offering.

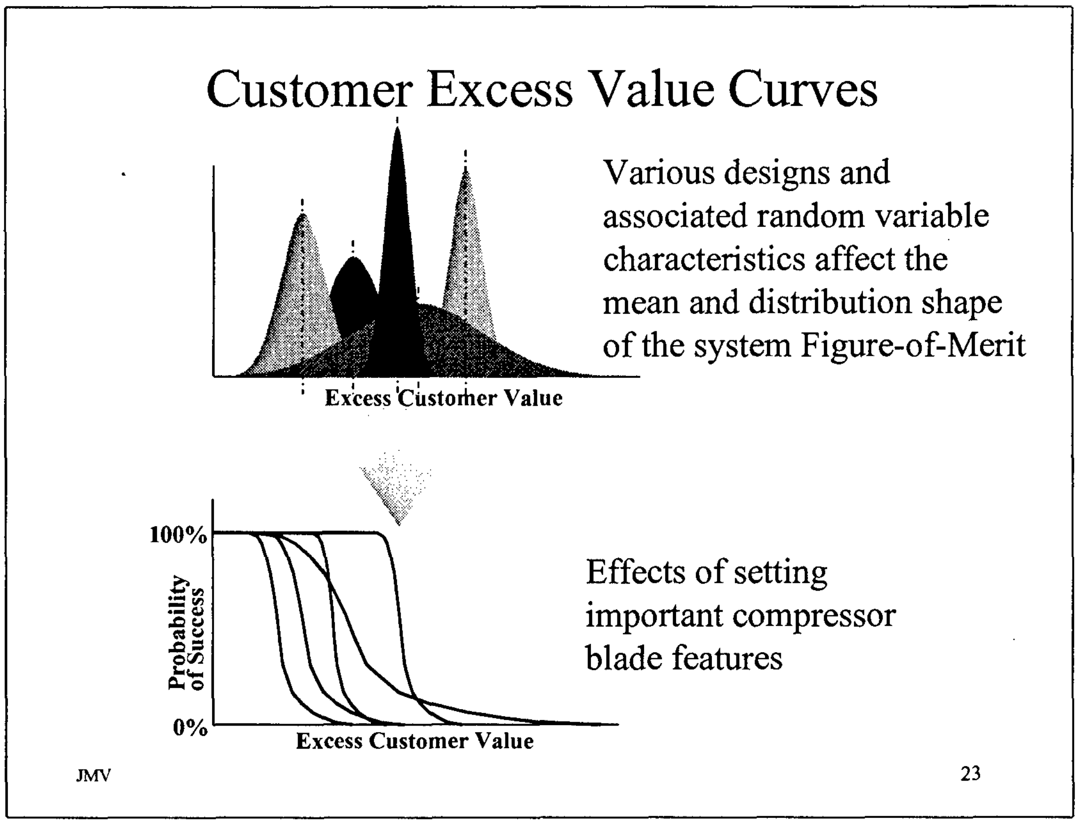
How Do We Determine What Could Change the Probability Curve?

... Explore the effects of compressor blade feature changes

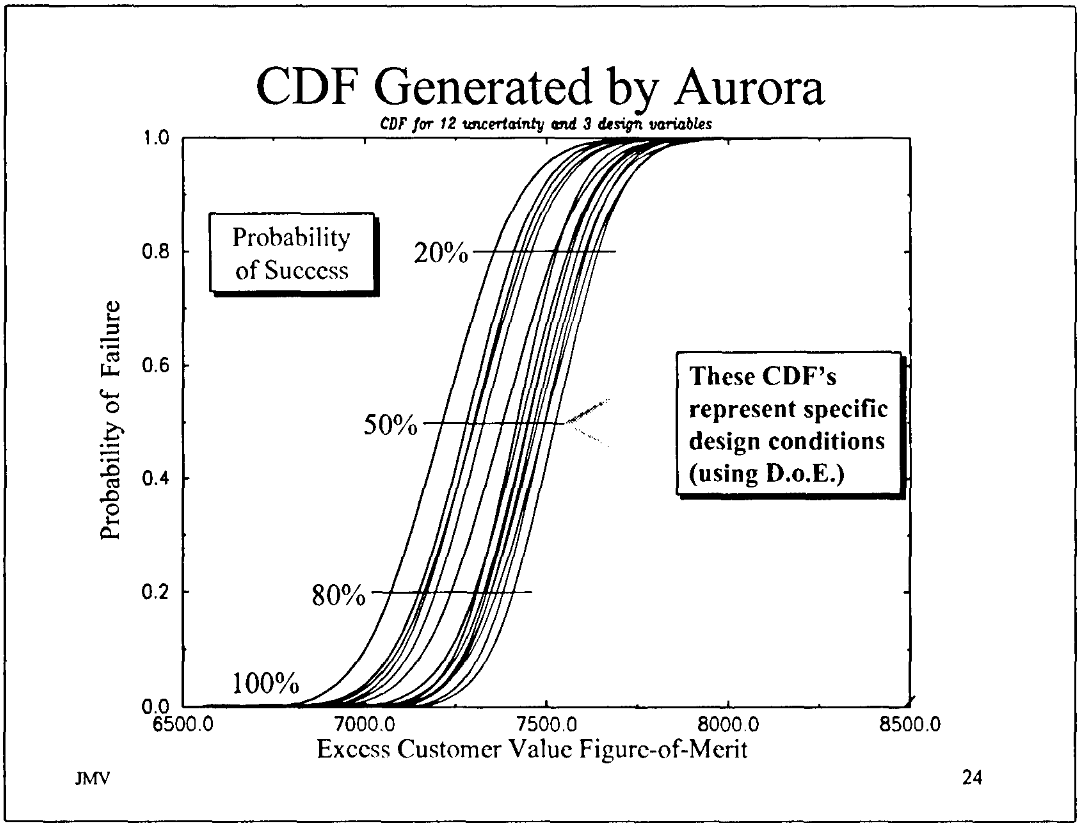
- Assemble Study Process
- Determine what features are important
  - D.o.E. screening could help do this
  - Probably different factors for different Figure-of-Merits (Cost or Performance)
- Identify Important Random Variables
- Determine Random Variable Distributions
- Apply Probabilistic Methods to Yield Cumulative Distribution Function
- Analyze Probabilistic Sensitivities to Determine CDF Shape Changes

JMV 22

The process is relatively straightforward. Screening Design-of-Experiments should always be conducted to help identify the most important elements that are affecting the system Figure-of-Merits. It should also be understood that several Figure-of-Merits may be monitored and that different elements may contribute heavily to these. The determination of the random variable distributions are usually the most difficult to obtain. These can be determined from additional simulations that have their own input random variables or from actual test, manufacturing, or product performance measurements. We have shown earlier that these characteristics contribute to the system Figure-of-Merit and can significantly shift and shape its distribution. The probabilistic sensitivities can then be analyzed to provide guidance for the shifting/shaping of the system Figure-of-Merit distribution.



The top illustration depicts the characteristics of the system Probability Distribution Function and is a function of the design settings and random variable distributions. This picture shows that the distributions are basically normal in nature but in reality could be any shape. The bottom illustration has converted the Probability Distribution Function's to (1-Cumulative Distribution Function). The resulting plot clearly indicates the situation that might be present to allow the trading of risk for large gains in customer value.



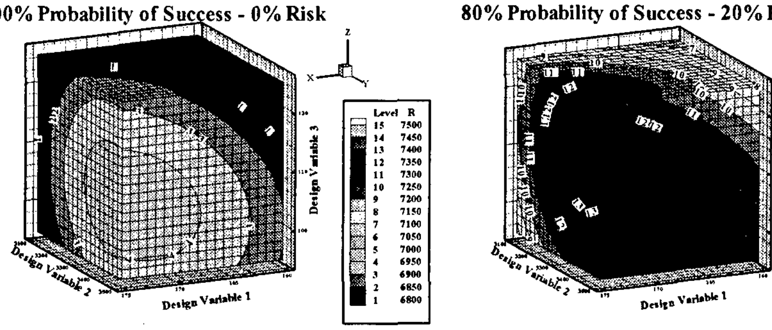
Data generated by applying the AURORA technique shows differences at specific design conditions. The data was generated at each point in a Design-of-Experiments spanning a range of engine design conditions. This data can now be used to explore the possibilities at various probability levels. For example, response equations can be created for the design space at 100%, 80%, 50%, 20% probability levels.

Study Objective

Find the Conditions That Meet Excess Customer Value Requirements and hold High Probability

100% Probability of Success - 0% Risk

80% Probability of Success - 20% Risk

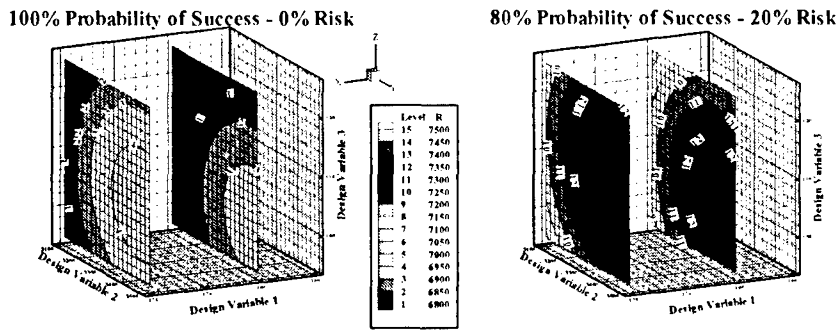


If Level 14 Values are Required, Then ...
Apply probabilistic sensitivities to create an area of Excess Customer Value

JMV 25

The above cubes represent excess customer value for combinations of three engine design variables and the color represents the magnitude of the excess customer value. Each cube represents 100% and 80% probability levels respectively. Other probability levels can be created if the additional risk is warranted. This data can be explored to determine the conditions that yield the desired excess customer value and the associated risk. Trade-offs can be made with different engine designs. Also, the associated probabilistic sensitivities can be utilized to make changes to the engine designs so that new or expanded regions of excess customer value appear.

Slices Through the Data Gives Some Insight Into the Extent of the Possibilities



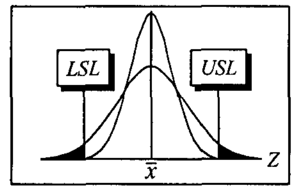
Can Make "Risk" Choices Based Upon Amount of Excess Customer Value

JMV 26

The cubes of data contain information that cannot be visualized just on the outer surfaces of the solid. Creating slices through the solids and viewing the results as contour plots yields additional information about the combinations of engine design variables. This data is an illustrative example of what can be accomplished and is based upon another system Figure-of-Merit. Usually several Figures-of-Merit are monitored and eventually constrained to yield suitable answers.

Additional Considerations

- What can be done to increase the insensitivity to variation?
  i.e. increase Z-Value



$$Z_{USL} = \frac{USL - \bar{x}}{\hat{\sigma}}$$

$$Z_{LSL} = \frac{\bar{x} - LSL}{\hat{\sigma}}$$

- If there are variation elements that our "System" is insensitive to, can we relieve the variation to save $?

Assumes that the original distribution has a cost associated with it and that relaxing the distribution can lower cost ... the original distribution carries with it some sort of control (machinery, tooling, operational practices, quality control, scrap, maintenance, service...)
... They all cost something

JMV 27

Insensitivity to variation or Robust Design can be considered when several solutions exist. Taking advantage of areas in the engine design space where variation insensitivity occurs makes the design less susceptible to missing performance, cost and weight. The Z-value metric is represented by the number of standard deviations that fit between the center of a process and a specification limit. Some variation can be considered as noise which we should not or do not want to control and others is a function of the process we use to design, test, manufacture, and maintain products. These variations also "cost" something and are the subject of cost savings if they are found to contribute little to the system Figure-of-Merit.

Summary

- *Common Geometry is an integrator of all product creation processes*
- *Common Geometry is an enabling technology for DFSS*
- *CAD Systems are evolving towards Intelligent Simulation Based Design*
- *A Product Data Management System providing a linked associative environment is necessary to propagate changes*
- *Parametric 3-D model construction is a prerequisite*
- *The probabilistic nature of the System Figure-of-Merit is a function of random input variables and can provide insight into risk taking*
- *Improvements to the the cost/benefit ratio are made by controlling or uncontrolling input random variables or by changing system requirements and assumptions*
- *Potential to provide feedback to the design community for the most basic design decisions that can directly impact the customer and maximize customer value*

JMV 28

Summary

- Common Geometry is an integrator of all product creation processes.
- Common Geometry is an enabling technology for DFSS.
- CAD systems are evolving towards Intelligent Simulation Based Design.
- A Product Data Management System providing a linked associative environment is necessary to propagate changes.
- Parametric 3-D model construction is a prerequisite.
- The probabilistic nature of the System Figure-of-Merit is a function of the random input variables and can provide insight into risk taking.
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- Potential to provide feedback to the design community for the most basic design decisions that can directly impact the customer and maximize customer value.

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This Lecture Series covers the recent advances in the process of performing integrated design of high performance multistage compressors.

The purpose is to broaden the compressor designer's understanding beyond traditional fluid dynamics to include the multidisciplinary systems approach required by modern gas turbine engines for longer life, lower acquisition and maintenance costs.

The design process requires an optimization of the entire machine, which may be significantly different from the best aerodynamic design of each stage or blade row. In addition, many modern engines are simultaneously increasing compressor performance, and reducing machine length, which reinforces the fluid and structure interactions. Finally, in order to reduce both production and maintenance costs, manufacturing constraints have to be taken into accout in the initial phase of the design process.

The Lecture Series underlines the role of Computational Fluid Dynamics, as well as solid mechanics and vibration simulations. The need for compressor designs to consider and model mechanical interactions and manufacturing concerns will be a central focus.

The subjects to be covered are:

- Flow simulations with special emphasis on three-dimensional computations and on the stage stacking and interactions in multistage compressors.
- Modelling the fluid structure interactions.
- First order manufacturing constraints and requirements.

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