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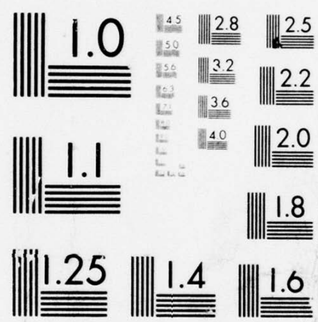

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FOREIGN OBJECT IMPACT DESIGN CRITERIA

Albert F. Storace

General Electric Company
Aircraft Engine Group
Cincinnati, Ohio 45215

October 1978

Interim Report 19 September - 31 December 1977

APPROVED FOR PUBLIC RELEASE
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Air Force Aero Propulsion Laboratory
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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This technical report has been reviewed and is approved for publication.

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This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The program objective is to develop and validate structural design criteria that account for the transient overloads by bird and ice impacts on turbine engine first-stage fan/compressor blades. A design system structure was completed. Work was started on development of transient response models and impact loading models. Tests and analyses to be used to generate local leading edge damage design data were defined. Planning was initiated for

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20. Abstract (Continued)

gross structural damage investigations and structural element tests. Formulation of a matrix for parametric analysis was started. Three first-stage blades were selected for modeling and testing.

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FOREWORD

This report describes the effort conducted under Contract F33615-77C-5221, Project 3066, sponsored by the Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio. The Air Force Project Engineer was Lt. Paul Copp.

The work was performed by personnel of the General Electric Company Aircraft Engine Group (AEG), prime contractor, and the General Electric Corporate Research and Development Center (CR&DC), and the University of Dayton Research Institute (UDRI), subcontractors. The General Electric Program Manager was Albert L. Meyer; the Technical Program Manager was Philip R. Holloway; the Principal Investigator was Albert F. Storace, who authored this report. The CR&DC efforts were under the direction of Dr. John P.D. Wilkinson; the UDRI efforts were under the direction of Dr. John P. Barber.

This initial interim report covers work performed during the period 19 September to 31 December 1977. Subsequent interim reports will be issued on an annual basis.

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1.0 INTRODUCTION

The objective of this program is to develop and validate structural design criteria that account for the transient overloads produced by bird and ice impacts on turbine engine first-stage fan/compressor blades. This program is part of a continuing effort of the Air Force to minimize ownership costs by placing added emphasis on the derivation of durable damage-tolerant advanced turbomachinery component designs.

Foreign object damage (FOD) in aircraft engines has been an increasing drain on defense economic resources. Present generation engine blading designs have substantial material toughness and cross section to meet the mechanical and aeromechanical requirements, but they were not specifically designed for damage tolerance. The prevailing design state of the art concerning damage-tolerant blading is mostly empirical and based on experience from major incidents and associated ad hoc testing. The empirical approach to designing damage-tolerant blading requires considerable investment of resources and is sometimes incapable of providing directly predictable foreign object impact response of blading. This approach is not adequate for newer, more damage-prone blading designs incorporating lightweight materials, including advanced composites, and thinner cross sections to achieve improved performance.

To achieve more efficient damage-tolerant blading, comprehensive foreign object impact design criteria, based upon transient structural response tools, are needed. These tools will provide direct assessment of a blade's impact damage tolerance and identify areas for improvement. The purpose of this program is to provide the necessary computer tools and validation testing to establish reliable foreign object impact design criteria.

This program consists of 11 tasks which progressively develop the FOD design criteria from computer models, structural element and material property tests, and static and rotating single-blade tests to full- or partial-stage rotating tests. The 11 tasks are identified as follows:

- Task I - Design System Structure
- Task II - Transient Response Analysis Model
- Task III - Impact Loading Models
- Task IV - Material Response and Failure Criteria
- Task V - Parametric Analysis
- Task VI - Structural Element Tests
- Task VII - Error Band Analysis
- Task VIII - Foreign Object Impact Design Criteria
- Task IX - Single-Blade Impact Tests
- Task X - Full-Stage Response Prediction
- Task XI - Full-Scale Impact Tests

The design analysis methods and failure criteria derived in the course of this program will be applicable to both advanced composite materials and monolithic materials of construction for current and advanced fan/compressor blading.

2.0 SUMMARY

The Task I effort to develop a design system structure was completed. A Research/Development Test Plan documenting the results was submitted to the Air Force for approval.

Work was started on development of the Task II transient response models; definitions of these models were submitted to the Air Force for approval.

Work was started on the Task III loading model development.

A Research/Development Test Plan defining the tests to be conducted and the analyses to be used in Task IV to generate design data for local leading edge damage was submitted to the Air Force for approval. Work was initiated on the R/D Test Plan for gross structural damage. Work was also started on the formulation of a parametric matrix that will define the conditions and geometries to be analyzed in Task V and on the structural element R&D Test Plan for Task VI.

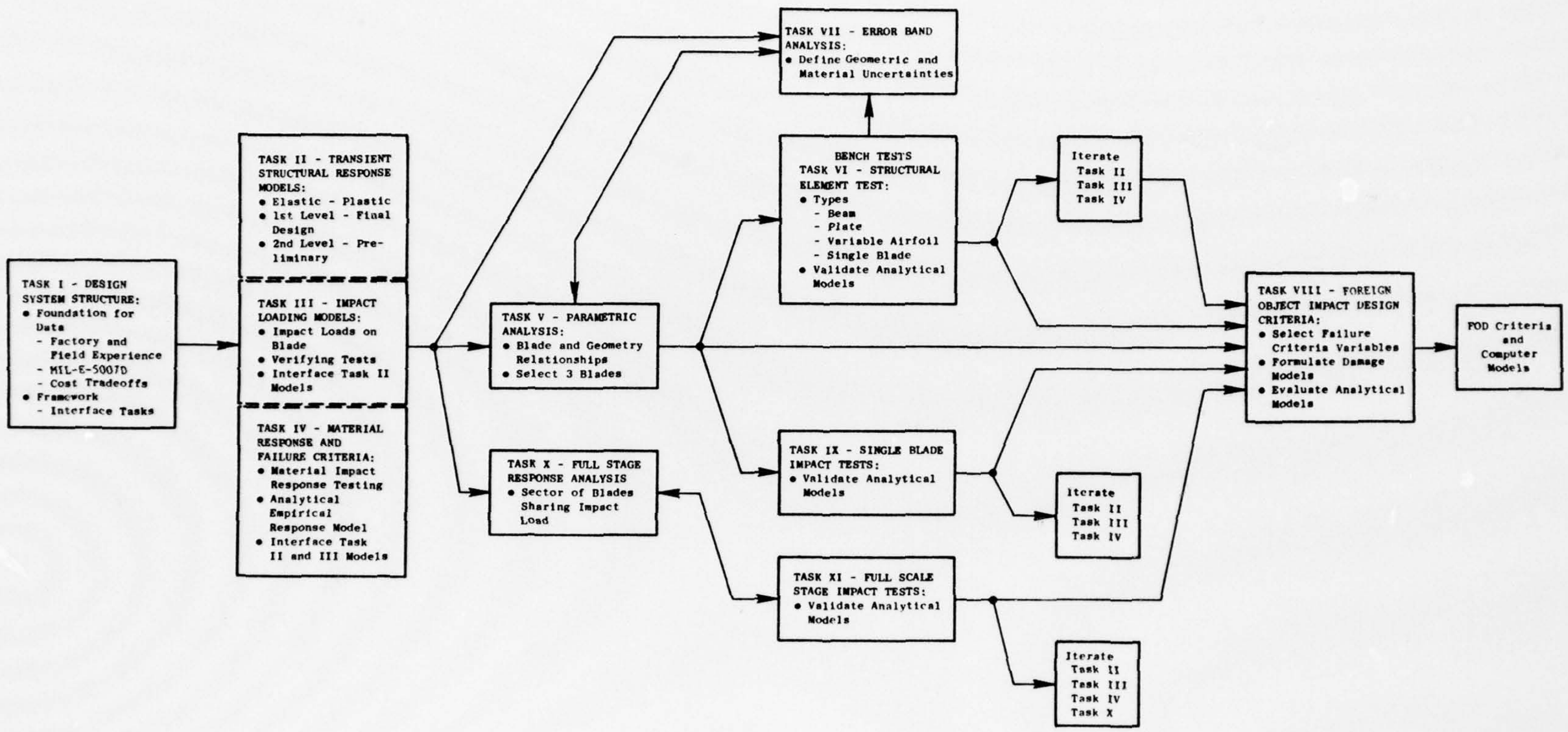
Three first-stage blades were selected for modeling and testing. These blades are the J79 Stage-1 steel compressor blade, the F101 Stage-1 titanium fan blade, and the APSI boron/aluminum fan blade.

3.0 TASK I - DESIGN SYSTEM STRUCTURE

A design system structure was developed through the Task I effort to establish a consistent framework in which to constitute FOD design criteria and guide the overall technical effort. This design system structure defines the objectives and interfaces of the various multidisciplined tasks that must be satisfied to achieve meaningful design criteria and includes a data foundation that describes the problem environment.

The figure on the following page depicts the interrelations between the major distinct activities of quantification of experience, analytic development, bench tests, rotating rig tests, and the workflow of the program.

The results of the Task I effort were documented in a Research/Development Test Plan that was submitted to the Air Force for approval.



Program/Tasks Flow - Foreign Object Impact Design Criteria.

4.0 TASK II - TRANSIENT RESPONSE ANALYSIS MODELS

The first- and second-level models selected for use in the transient response analysis of fan and compressor blades were submitted to the Air Force for approval.

4.1 FIRST-LEVEL RESPONSE MODEL

The finite-element method of structural analysis will be used for the first-level (final design) response model, and the NONSAP finite-element computer program was selected as the basis for this model.

A study was completed to determine the types and the range of applicability of the 3-D elements available in the version of NONSAP that will be used for the first-level analysis. The 3-D elements available can be assigned from 8 to 21 nodes. These elements are all conforming, isoparametric elements. It was concluded from the study that the 20-noded 3-D element is the only acceptable way to model in the regions of the elastoplastic action. The material modeling capability of the NONSAP program will be expanded to allow the analysis of anistropic material yielding.

Attention was directed to possible methods for including strain rate effects in the elastoplastic constitutive relations. One method that will be investigated involves the use of strain-rate-dependent stress/strain curves such that a different stress/strain curve is used at a particular time step based on the strain rate in the individual elements.

An alternate method for including the strain-rate sensitivity, involving the use of different constitutive curves in different areas of the model, will also be studied. The curves would not change with time; thus, there would be a reduction in the number of iterations needed to obtain a solution. Based on experience or an initial analysis, these curves would be chosen to reflect, in an average sense, the variation in strain rates which would appear in the blades.

With the help of Professor Bathe of MIT, the logic for the addition of centrifugal effects to the NONSAP code was completely outlined. The modifications will require two new subroutines. One subroutine will calculate the centrifugal load vector. The second subroutine will use that load vector to calculate centrifugal displacements which will then be used as initial conditions for the transient response. The constant centrifugal loads will also be added to the impact loads for each time step. This formulation will also result in the calculation of eigenfrequencies and eigenmodes which will indicate the effects of centrifugal stiffening. The first draft subroutine to calculate centrifugal loads has been written. The subroutine to use these loads to calculate the set of initial conditions has been completed with the exception of some details concerning memory space.

The revised version of NONSAP was tested on a problem previously analysed with ADINA. The problem analyzed was the two-element model of a thin plate under impact which is discussed in the proposal. The results obtained from the revised version agree with the previous work, indicating that a working version of the routine is in hand.

4.2 SECOND-LEVEL RESPONSE MODEL

General Electric's COMET computer program was selected as the basis for the second-level (preliminary design) response model. The COMET program is based on the component element method and has been found to be amenable to nonlinear dynamic studies in a variety of fields.

The additional elements which must be developed for the second-level analysis model were defined, and implementation of these elements was begun in the existing COMET-PIPE program. This program already contained the desired input-output and time-integration routines. The most important part of incorporating the new elements into the component element framework is the formulation of what is referred to as the "coupling coefficients." These coefficients couple nodal displacements to the generalized element elongations, and they couple the generalized elongations to the nodal forces. Several of the subroutines necessary for generating these coupling coefficients have been written in rough draft.

The formulation and programming of the plate-bending-type elements for the blade was completed including obtaining principal bending moments in the plastic range and nodal loads. The nine-noded element takes care of three cases; (a) an element around a central node; (b) a corner element; and (c) a middle-of-a-free-edge element. An additional element, also applicable into the plastic range, was formulated for built-in edges or edges restrained by another structure. The new elements are now being incorporated into the basic COMET program, and the data for a trial analysis is being prepared.

5.0 TASK III - IMPACT LOADING MODELS

5.1 INTRODUCTION

Overall planning and assessment of Task III was accomplished, and work was conducted on the three subtasks as described below.

5.2 SUBTASK A - COLLECT AND AUGMENT DATA BASE

The collection of pressure plate data was started. These data will be used to augment pressure plate data for microballoon gelatin and ice at various impact conditions acquired on previous programs. The range was assembled and approximately 30 % of the shots in the shot matrix were collected. In these shots, the surface plane of the pressure plate was normal to the projectile trajectory. The remaining shots on this task will be conducted with the surface plane of the pressure plate at angles of 45° and 25° to the trajectory of the projectile. At the completion of the microballon ozelation and ice pressure loading test program, a report will be issued. This report will include a comparison between the measured impact loads obtained for the gelatin bid substitute and for real bids.

5.3 SUBTASK B - SENSITIVITY STUDY

The MARC/CDC finite-element code is being used for the numerical analysis in the sensitivity study. The first runs of the program will use only linear analysis to compare the effects on a cantilever plate of the various spatial and temporal loading distributions. If the deflections and strains obtained using this analysis are not too large to invalidate the linearity assumption in the finite-element code, then a nonlinear analysis will not be needed. However, preliminary estimates lead us to believe that most of the loading conditions will exceed linear analysis accuracy, at which point it will be fairly simple to adjust the finite-element code for nonlinear analysis and improved results.

5.4 SUBTASK C - FORMULATION OF LOADING MODELS

Work on the bird-impact modeling effort progressed along two fronts. First, the theoretical methods which serve as the basis of the present model (valid for round jets impacting on flat plates) were extended to include curved surfaces. The present model for the steady-flow phase of a bird impact is based on a superposition of two potential flow solutions, one being an axisymmetric, uniform, round jet, and the other being the flow caused by a uniform surface distribution of sources over an area defined by a plane intersecting the round jet. This area is elliptical in shape. The extended model again is obtained by superposition of a round jet and a surface distribution of sources over the area defined by the intersection of the jet with the curved surface. In the extended model, the surface distribution is nonuniform, but determining the distribution of the source strength does not involve matrix algebra, rather, just simple summations.

In addition, we are investigating the use of surface distributions of doublets rather than surface distributions of sources. The rationale for attempting to use doublets is that, from the general theory of potential flow, it is known that doublet surface distributions can be used to represent vortex sheets. The boundary of a free jet in potential flow is a vortex sheet. Thus there is some hope that our model of jets impacting on surfaces can be improved by using doublet surface distributions.

The analytic integrations required to determine the velocity field induced by a uniform distribution of doublets were not commpleted. Closed form solutions appear to be attainable, however, and so this effort is continuing.

The second effort was an attempt to improve the present model. The present model breaks down around the periphery of the impact region. We have investigated, and are continuing to investigate, methods for eliminating the shortcomings of the present model. Improved accuracy can be obtained by using surface signularities to represent the origin of the jet flow, as well as the flow on the impact surface itself. This improved accurracy is obtained at the expense of a considerable increase in computational effort, principally in terms of the requirement that a large, nonsparse matrix must now be inverted. Efforts are now being directed toward determining if the added accuracy is cost-effective.

6.0 TASK IV - MATERIAL RESPONSE AND FAILURE CRITERIA.

6.1 SUBTASK A - GROSS STRUCTURAL DAMAGE PROPERTIES

There are two parts to the testing that will be performed to establish gross structural material response and failure data. First, impact tests will be conducted using full-scale blades. These tests will allow determination of the strain rates pertinent to the problem of foreign objects impacts. The impact tests will be conducted on three different type blades, two of which are unshrouded. The two unshrouded blades are the stainless steel J79 first stage compressor blade and the B/Al composite APSI first stage fan blade. These blades will be cantilever mounted at the coat. The third blade type is the titanium F101 first stage fan blade. This blade is tip shrouded and therefore will be fastened at both ends. Each blade type will be impacted at the 30 and 70 percent span locations. Two blades of each blade type will be used for the impact tests.

In the second part of Subtask A, material property data will be obtained for the relevant strain rates.

The specimen design and testing procedures for the metal tests have been established. Forged bar stock will be used to make the metal specimens. The tests will be conducted on 8Al-1Mo-1V Titanium and 403 Stainless steel.

A standard cylindrical specimen will be used for the tension tests at low and intermediate strain rates. The entire stress-strain curve will be obtained using strain gages and an extensometer. Poisson's ratio will be calculated using the change in diameter. The high strain rate tests for the metals will be conducted on the split-Hopkinson bar using the standard tension test specimen for that apparatus.

The advanced composite selected for the study is boron/aluminum used in the APSI Stage 1 fan blade with a fiber layup of [0/22/0/-22]. The 4-mil boron fibers are in a matrix of 2024 aluminum. Each plug is 4.7 mils thick and does not, in general, run the length of the blade. The center ply of the blade is a plate of aluminum. On either side of it is a ply of stainless steel wire meals. The next plies on both sides are the B/Al layup. The entire outer blade surface is covered with a ply of stainless steel wire mesh. The leading edge has a thin coat of pure nickel.

The material properties are needed in three principal directions because the composite is anisotropic. The data needed are the tensile stress-strain curves for each duration, three Poisson's ratios, and three shear stress-strain curves. However, the collection of this information is simplified considerably by the use of laminate theory. This theory employs the results of material property tests on unidirectional specimens to calculate the bulk properties of the angle-ply layup.

A study effort is currently underway to define the composite specimen design and the experimental methods that will be employed to obtain the composite material properties.

6.2 SUBTASK B - LOCAL LEADING EDGE DAMAGE

A Research/Development Test Plan entitled "Task IV, Subtask B - Local Leading Edge Damage" was submitted to the Air Force for approval. This test plan describes the tests to be conducted and the analyses to be used to determine and quantify the damage caused by leading edge impacts for a range of pertinent impact conditions. The results of this subtask will be used to generate design data that is expressed in terms of the residual properties of fan blade materials.

The impactors for the study include 1.5-pound birds, 2-3 ounce birds, 1/4-inch diameter pebbles, 60-mil glass beads, 30-mil glass beads, 1-inch diameter ice spheres, and 1-inch diameter by 4-inch long ice cylinders micro-balloon gelatin material will be used to simulate actual birds.

The impact velocities planned for this investigation will correspond to those which would be typical of an impact at 70 percent span and at 30 percent span at full power settings of the engine during takeoff on each of the 3 blade types selected for the program. Impacts at 70 percent span are representatives of the highest velocity impacts experienced by a blade. Impacts at 30 percent span are typical of those in the highest stress regions of the blade.

The leading edge specimen (targets will simulate the leading edge geometry and thickness of typical actual blades of the same material at the 50 percent span level along the leading edge. This will limit the number of required tests. Since these specimens are only approximate shapes, the small variances between 30% and 70% span locations is not critical. No camber or twist will be incorporated in the specimen.

7.0 TASK V - PARAMETRIC ANALYSIS

7.1 BLADE SELECTION

Three first-stage blades were selected for modeling and testing and the selection will be submitted to the Air Force for formal approval. These blades, representative of first-stage airfoils from Air Force inventory, production development, and advanced development engines, include subsonic, transonic, and supersonic airfoil shapes and stainless steel, titanium, and an advanced composite material, respectively.

The blades selected by General Electric are listed below:

Blade	Representing	Airfoil	Material	Shrouded
J79	Air Force Inventory	Subsonic	Stainless Steel	No
F101	Production Development	Transonic	Titanium	Yes
APSI	Advanced Development Supersonic Engines	Supersonic	B/Al Composite	No

7.2 PARAMETRIC MATRIX

Work was started on the formulation of the parametric matrix that will be used to define the conditions and geometries that will be analyzed in Task V. The final form of the matrix will be dependent on the decisions made as to the types of specimens that will be fabricated for the structural tasks to be conducted in Task VI.

The matrix will encompass simple impact conditions, impact conditions which are more representative of actual airfoil FOD dynamics, and target elements ranging from plates and beams (that include a progressive introduction of airfoil geometric features) to the three selected first-stage airfoils in stationary and rotating environments. The parametric matrix will be submitted to the Air Force for approval.

8.0 TASK VI STRUCTURAL ELEMENT TESTS

Work on the Task VI Research/Development Test Plan was started. In discussions between GE and UDRI, it was established that because of the high cost involved it would not be practical to introduce camber and twist in all of the structural test specimen categories. The camber and twist parameters are not cold-formable on the titanium specimens, and special dies would be required to achieve these geometric features for the composite specimens. For the titanium specimens, the camber and twist would be possible only through hot-forming or machining operations. However, for the steel specimens, the desired geometric features could be obtained through cold forming. Further investigations will be conducted to determine the metal and composite specimens that can be fabricated for Task VI, consistent with the scope of the program.

During testing of the structural specimen, the different geometry effects (i.e., aspect ratio, thickness/chord ratio, etc.) will be introduced in a different sequence for the titanium and steel specimens so that any synergistic effects that might exist can be accurately assessed.