Analytical and Experimental Investigation of Bird Impact on Fan and Compressor Blading

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An analytical design tool and structural design criteria have been developed to assess and improve the foreign object damage (FOD) tolerance of turbine engine fan and compressor blading The analytical method is based on a three dimensional finite element computer code that incorporates an interactive bird-loading model The computer code and design criteria provide a systematic transient structural analysis approach that will aid in the design of structurally efficient, impact damage resistant blading

Introduction

A THREE DIMENSIONAL and nonlinear finite element program has been adapted for the purpose of studying the response of fan and compressor blading to bird impact The NOSAPM transient structural analysis computer program is a version of the NONSAP code that includes an interactive bird loading model the initial state of stress, and the nonlinear stiffening effects due to the centrifugal loads on a rotating blade This computer program and the ac companying blade failure criteria have been developed under the Air Force sponsored Foreign Object Impact Design Criteria Program (Contract F33615 77 C 5221) Both NOSAPM and the time dependent structural design criteria account for the transient overloads on blading that are produced by bird impact The objectives of the investigation and development effort are to replace empirical trial and error foreign object damage test and evaluation practices with systematic transient analysis methods and design criteria During the course of the program, a large volume of ex perimental data has been accumulated on materials, specimens and engine blades Static bench impact testing of airfoil like specimens and rotating single blade and full stage impact tests have provided excellent controlled results, and comparison of these results with the predictions has shown excellent agreement Based on this experience the use of NOSAPM and the associated design criteria will provide the designer with the analytical capability to calculate post ingestion damage and thus establish the design features needed to design more efficient damage tolerant blading

Analytical Approach

The transient response due to bird impact on fan and compressor blading is analyzed with a modified version of the finite element program NONSAP [1] This program is capable of carrying out a very detailed analysis embracing local impact damage as well as gross structural damage NONSAP is a very general and accurate package for nonlinear, finite element analysis and employs three dimensional (3 D) elements The modified version is called NOSAPM and this program incorporates an interactive bird loading model based on a fluid flow concept and includes the nonlinear stiffening effects initial displacements and initial stresses due to the centrifugal loads on a rotating blade. The modifications in NONSAP which were implemented in order to achieve these capabilities have been previously discussed in Refs 2 and 3 where the results of impact analyses on simple plate like shapes were also presented This work has been extended to the analysis of real blade impacts, as well as damage criteria used in structural design analysis of blading subjected to bird impact In addition, test data are presented that verify the accuracy of NOSAPM and the structural design criteria used to predict damage resulting from bird impact on real blades

The loading model treats the bird impact as a fluid dynamic process and this is consistent with the experimental ob servations of Barber, Wilbeck and Taylor [4] Similarly, Alexander and Cornell[5] and Engblom[6] have used a fluid dynamic model to establish the loads resulting from bird impact on blades The NOSAPM bird loading model was developed by Boehman and Challita[7] at the University of Dayton Research Institute and it expands upon the work reported in Ref 4 for impact of rigid targets to include the interactive effects of impact on a compliant target The bird impact is modeled as a fluid jet impinging on an arbitrarily shaped three dimensional deformable surface A quasisteady, potential flow analysis is applied to the jet impact problem thereby reducing the impact problem to the problem of solving Laplace's equation The initial shock (Hugoniot) pressure is not included However, experimental pressure measurements in Ref 4 indicate that for the oblique impacts typical for bird ingestion, the largest contributing factor in the total impulse of a bird impacting a target is the steady flow phase of the impact The loading model is configured to include the steady flow regime and it is incorporated in the NOSAPM code as a subroutine that uses the instantaneous impacted surface shape and velocity to automatically characterize the pressure distribution The pressure distribution is then converted to equivalent nodal forces through a consistent force formulation The loading model is capable of detailed interaction with the structural response, as well as dealing with target translation rotation, and local deformation In the loading model used for full stage or design analysis the bird is idealized as a right circular cylinder and the velocity of the bird relative to the aircraft is taken to be equal and opposite to the aircraft velocity In this model the thickness of the bird slice is defined by the cutting actions of the target blade and the blade leading the target blade The bird/blade interactive geometry for this case is shown in Fig 1 The orientation of the axis of the bird and the center of impact of a slice are chosen to produce a slice having the largest possible mass The largest slice mass occurs when the axis of the slice is coincident with the axis of the right circular cylinder The slice geometry depicted in Fig 1 corresponds to

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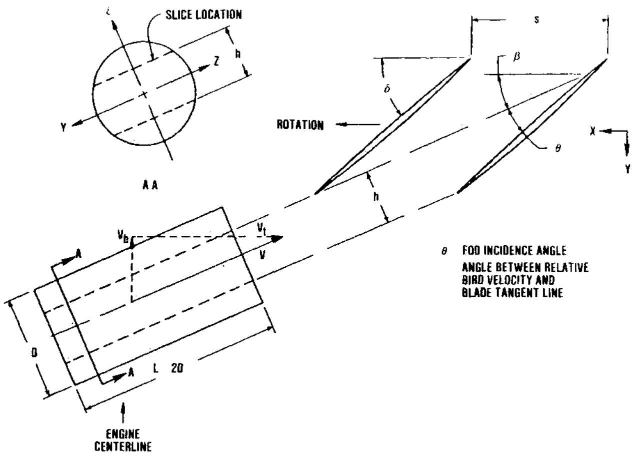

Fig 1 Soft body impactor definition for full stage analysis For full stage analysis, the bird is idealized as a right circular cylinder with a length to diameter ratio of 2. The orientation of the axis of the bird is chosen to produce a slice having the largest possible mass.

this worst case situation The loading model is also capable of modeling single blade whirligig and bench impact In the former case, the target blade slices a static impactor projected into the path of the blade with the relative velocity equal to the tangential velocity of the blade resulting from the wheel angular velocity In the latter case the target blade is stationary and the slice thickness and the impact velocity are defined by the original size and velocity of the impactor

The NOSAPM program provides the geometric and material nonlinear analysis capability needed to address the large displacement, elastoplastic behavior that is charac teristic of the transient response of first stage fan and compressor blades due to foreign object impact This program employs three-dimensional (3 D) isoparametric finite elements that can be used with a variable number of nodal points ranging from 8 to 21 Based on cost and con vergence studies,[8] it has been determined that the use of 16 node elements (mid sided nodes in the blade in plane direc tions and corner nodes in the thickness direction) provides an accurate and cost effective modeling approach for blades Brown and Krahula,[9] and Engblom[6] have used plate elements to model blades subjected to impact and have reported good results Obviously, there are trade offs between the use of plate and solid brick elements relative to cost, accuracy, and modeling detail However, we have found that the solid element used in NOSAPM provides the capability of modeling blades with a relatively coarse mesh size (typically, less than 80 elements are required) and no marked change in the results occurs for fairly substantial changes in the mesh definition in areas outside of the impact zone In the three dimensional element formulation used in NOSAPM the inelastic material behavior is modeled with a bilinear stress strain curve and both isotropic and kinematic hardening are available for application Centrifugal stiffening has been incorporated in NOSAPM through the addition of a body force (centrifugal) load vector The centrifugal load is applied statically in 5 steps and the stiffness matrix is reformed at each step based on the current deformed geometry; because the stiffness matrix is modified in small increments, no iteration is required This approach insures that equilibrium is satisfied when the full centrifugal load is acting on the blade The result is a centrifugally stiffened blade which is in an initial displacement and strain state This initial state is used to define the initial conditions for the dynamic analysis In essence, a two step process is used for FOD analysis in NOSAPM The first step is incremental static analysis to determine the centrifugally stiffened stiffness matrix the centrifugal forces acting on the nodes, the initial displacements and the initial strains The second step is

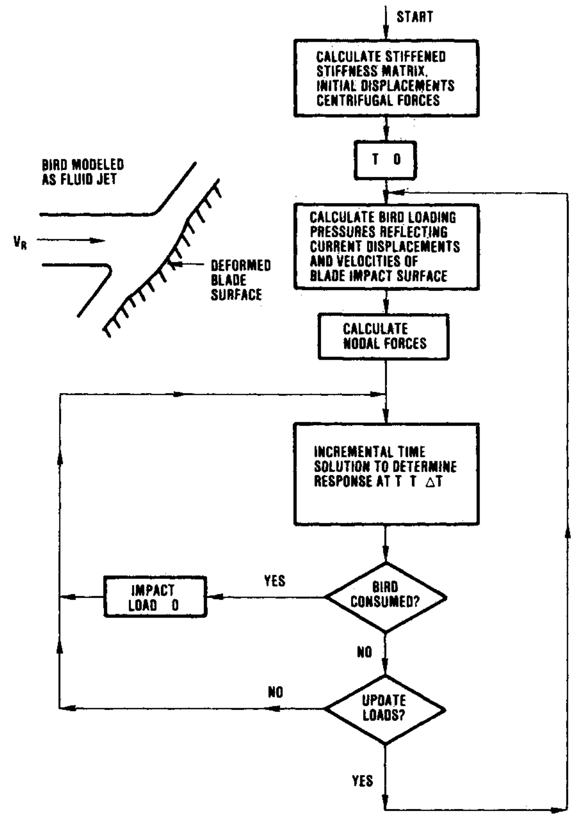

Fig 2 Flow chart for load response interface in NOSAPM

Table 1 Design criteria

Limit local plastic deformation to a specific percentage of chord to avoid stall/surge
Limit strains in the impact region in order to avoid tearing and mass loss
Limit strains at the root of the blade in order to prevent airfoil loss
Limit displacements in order to avoid contact with adjacent blades and stages

application of the dynamic bird loads to the blade in the impact region Starting transients due to the initial centrifugal displacements are avoided by applying the constant cen trifugal loads to the blade at each time step of the dynamic analysis The load response interface and the incremental solution approach used in NOSAPM are depicted in Fig 2 In addition, the centrifugal displacements calculated for the initial state of the blade before impact are also utilized in the calculation of eigen frequencies and eigenmodes which in dicate the effects of centrifugal stiffening

Structural Design Criteria

Design criteria have been developed which utilize the geometric and material nonlinear analysis capabilities available in NOSAPM The design criteria are listed in Table 1 and the damage variables addressed include surface prin cipal strains, local plastic deformation such as bulging, and overall blade displacements resulting from far field structural response The surface maximum and minimum principal strains are used in conjunction with a forming limit concept whereby the relative values of these strains are compared to a failure boundary or forming limit diagram (FLD) to establish if tearing and possible mass loss occurs

Figure 3 shows a graphical presentation of the criteria for tearing This figure shows the strain failure boundary for the

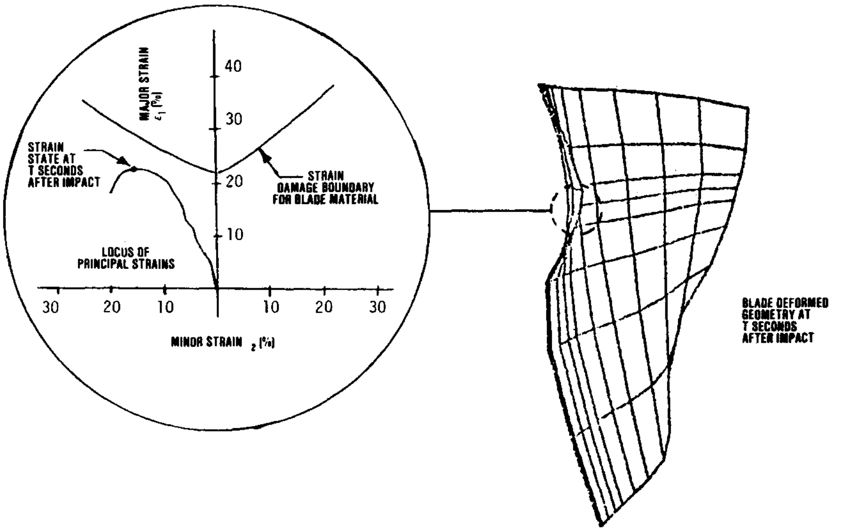

Fig 3 Criteria for tearing—computed principal strain states compared to damage strain boundary defined by material forming limit diagram (FLD)

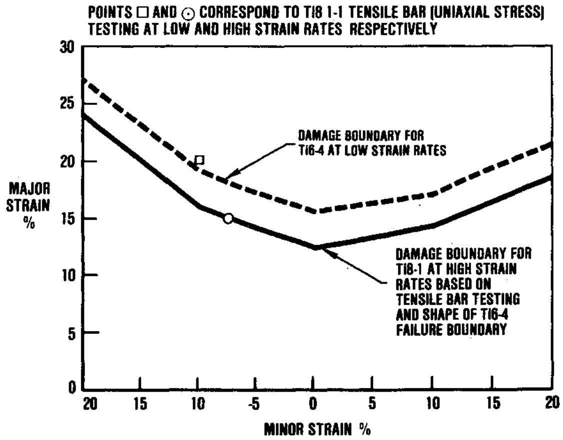

Fig 4 Estimated damage boundaries for Titanium 8AL $1M_0$ 1V at low and high strain rates

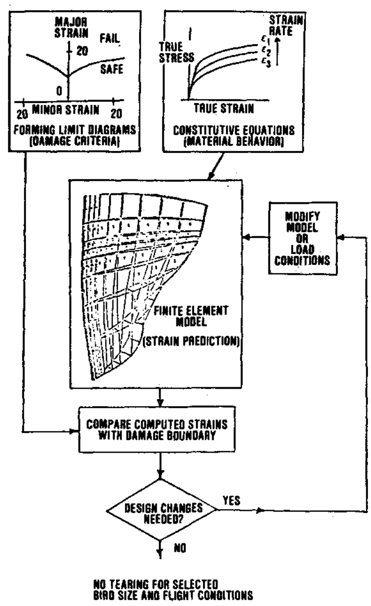

Fig 5 FOD design and analysis steps to avoid tearing

blade material and the locus of computed surface principal strains at the impact site In this figure, the strain locus does not cross the FLD failure strain boundary, hence, tearing is not predicted to occur It will be noted that forming limit diagrams are typically used in predicting formability in the manufacture of sheet metal parts and are obtained through low strain rate (in the range 10^{-2} to 10^{-1} sec^{-1}) experiments using the Punch Stretch Test In this approach, a punch is utilized to deform sheet metal specimens to the onset of failure and photoetched circular grids on the sheets are used to determine the final strain distributions Different ratios of major to minor strains, or the states of biaxiality are achieved by varing the size of the sheet specimen from a narrow strip to a square strip When visible necking or failure is observed on the sheet, the combination of major strain, ϵ_1, and minor strain ϵ_2, is measured After repeating similar tests over various strain states, the loci of failed and unfailed regions is established on the ϵ_1 ϵ_2 plot and this is called the forming limit diagram The strain rates pertinent to soft foreign object impacts determined with real blade bench impact tests per formed by Bertke[10] approach 400 in /in /s Tensile bar testing at low intermediate, and high strain rates (range = 100 1000 in /in /s) performed by Emery[11] indicates that the failure boundary strain values decrease with in creasing strain rates Figure 4 shows the failure boundaries for Titanium 8 AL $1M_0$ 1V (blade material of one of the blade types tested in this program) at low and high strain rates The strain failure boundary for low strain rates is based on the FLD for Titanium 6 AL $4M_0$ obtained from the Punch Stretch Test[12] and tensile bar test results at low strain rates[11] for Titanium 8 AL $1M_0$1V This data indicates that the FLD for Ti 8 1 1 and Ti 6 4 are similar at low strain rates The strain failure boundary for high strain rates was developed by assuming that the failure boundary shape is the same as that for low strain rates, and the location on the strain map was established using the results obtained from split Hopkinson bar testing [11] Analysis results are presented below for a full stage impact that utilize the high strain rate damage boundary for Ti 8 1 1 shown in Fig 4 It is shown that the predicted strains cross the damage boundary, indicating tearing and this agrees with the results obtained from the actual impact testing Figure 5 depicts the design and analysis steps to be followed to avoid tearing

It was found that the NOSAPM code and failure criteria developed with large engine data and analysis correlation are applicable to small engines However for small engines larger populations of airfoils in a cascade are involved in the impact sequence Therefore, more blades suffer plastic deformation and this results in greater postingestion performance concerns than for larger engines

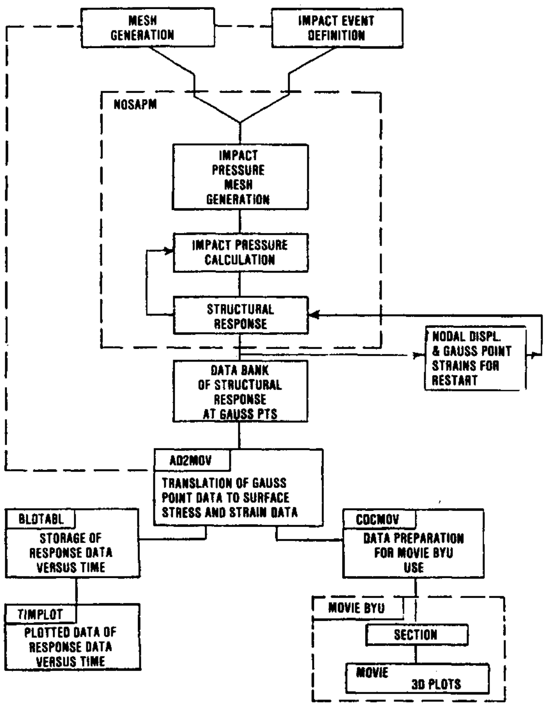

Fig 6 NOSAPM analysis system

Analysis System

The NOSAPM analysis system is shown in Fig 6 In ad dition to the NOSAPM base program, this system includes mesh generation and data preparation programs and a comprehensive graphics package It will be noted that computer graphics is a must for meaningful interpretation of the voluminous amount of data produced by NOSAPM The blade geometry and impact conditions are defined with a preprocessor or data deck generator program This program generates card images of the NOSAPM input data based on element and node files created with a mesh-generator program and also, on user input specified in the interactive time sharing mode The memory required for the NOSAPM program on the CDC7600 computer is 305,051 octal words NOSAPM is run in the batch mode and the output is stored as a data bank on disk space Referring to Fig 6, this data bank is processed with the program AD2MOV to transform Gauss point stresses and strains into surface stresses and strains The program BLDTABL is used to format the output from AD2MOV and to create the files needed for the plotting program TIMPLOT Then, in the interactive mode an analyst can plot the surface strains and stresses or displacements at any of the model nodes Once critical times during the impact have been identified, three dimensional deformed geometry and contour plots can be generated by running the CDCMOV and MOVIE[3] programs CDCMOV is an interface program that structures the data generated by AD2MOV so that it is in a form suitable for MOVIE The MOVIE system consists of a compatible set of FORTRAN computer programs which facilitate the display of finite element models The system is designed around a program which generates line drawings and continuous tone shaded images It also includes routines which are used to organize and modify user data files, process three dimensional models in order to expose selected interior surfaces, and generate characters for title purposes

In addition to the capabilities discussed above, NOSAPM has a restart option that allows the utilization of the results obtained from a previous analysis to continue the analysis out to future time This allows NOSAPM to be run in segments so that if, for example, the blade response at a time beyond that originally specified is desired, then the program need not be rerun from time equal to zero out to the new time desired At

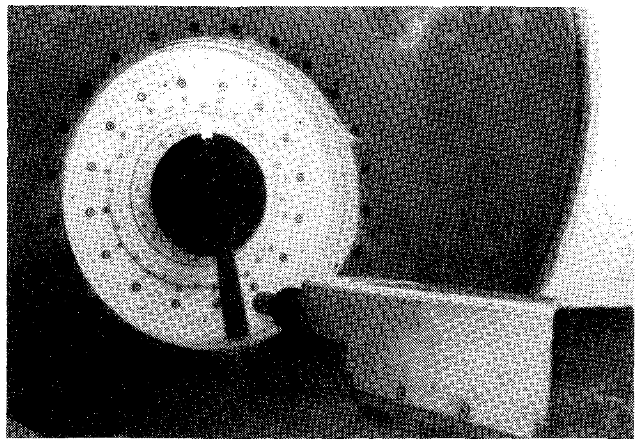

Fig 7 Blade and injection mechanism used in single rotating blade whirligig impact test

the end of a given analysis, the NOSAPM program can be directed to send to a file the displacement and strain data needed to restart the analysis This information can then be utilized to provide the initial data needed to continue the analysis and the process can be repeated any number of times

Blade Impact Modeling and Analysis Validation

The primary response modes for blades undergoing soft body impact are bending and stretching Thus, one element through the thickness was used to model the blades under investigation in this program As previously mentioned, the element type selected is the 16 node isoparametric finite element The fully nonlinear bird loading interactive analysis capabilities of NOSAPM were utilized to simulate ex perimental impacts for single blade static and rotating cases, and for a full stage of fan blades

Figure 7 shows the whirligig impact test set up for a first stage compressor stainless steel blade In this single rotating blade impact test, a "fixed bird" method is used in order to exert maximum control over the size of the impactor Microballoon gelatin material is used to simulate the bird and a cylindrical impactor constructed of this material is secured to a mechanical injector and inserted to a predetermined depth in the blade's path The blade then "bites off" the impact object and the mechanism retracts the residual por tion Spatially and temporally resolved pressure measurements made by Bauer and Barber[14] for impacts of artifical (microballoon gelatin) birds and real birds on rigid targets indicate that gelatin behaves the same as real birds during impact The blade and disk setup and the injector mechanism used to project the bird into the path of the blade are shown in Fig 7 Figure 8 shows the NOSAPM model of the blade For the plane of the blade, a 2 × 2 Gaussian in tegration configuration was used, while three Gauss points were used through the thickness This selection resulted in smooth and well behaved stress distributions over the elements The analysis strategy was as follows

1) Initial conditions were based on the nonlinear cen trifugal stiffening calculation

2) Initial displacements were equal to centrifugal displacements (at $T = 0$)

3) The centrifugal force vector was added to impact loads at each time step

4) Fully geometric and material nonlinear impact analysis with stiffness matrix reformation was conducted for each time step

5) A bilinear material model and the isotropic hardening rule were used to represent the elastic plastic behavior of the 410 stainless steel material

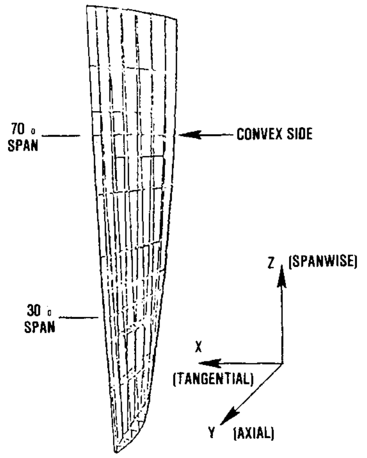

Fig 8 NOSAPM 77 element finite element model of airfoil used in simulation of whirligig impact test

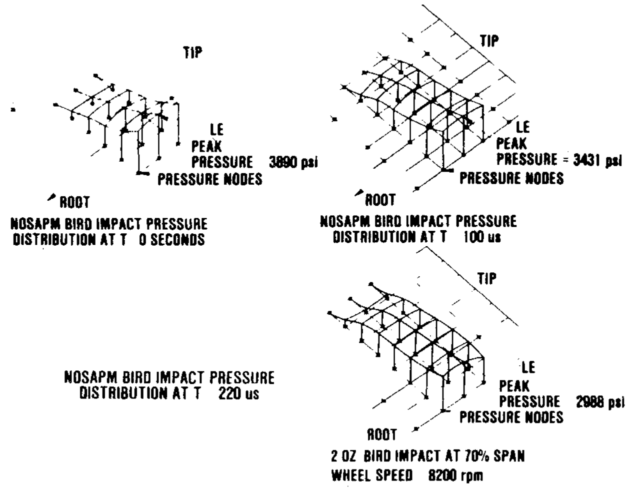

Fig 10 Computed bird loading pressures for whirligig impact test simulation

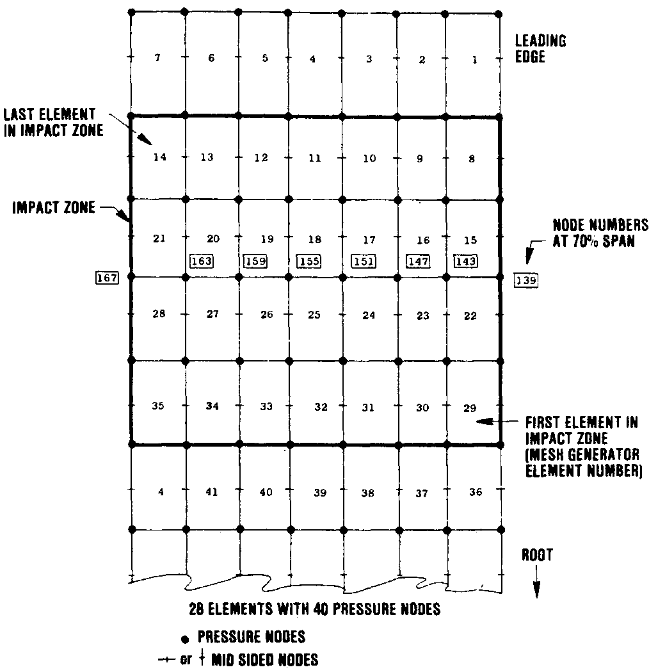

Fig 9 Designated impact zone and pressure nodes used in the NOSAPM analysis of the airfoil

6) The following material properties were obtained from Ref 11:

E_1 = primary modulus = 28×10^6 psi
E_2 = secondary modulus = 250 000 psi
σ_{YP} = dynamic yield point stress = 120,000 psi
μ = Poisson's ratio = 0 297
ρ = density = 0 2749 lb/in ^{3}

7) Newmark time integration method ($\delta = 0\ 5$ $\alpha = 0\ 25$) with time step $\Delta T = 10\ \mu s$

8) Three solution segments (2 restarts) $0 \rightarrow 300\ \mu s$, $300 \rightarrow 650\ \mu s$, $650 \rightarrow 1010\ \mu s$

9) Interactive bird loading pressure calculation specified for each step

The approach used to model the impact is now described The selected impact region is shown in Fig 9 This is a designated zone sized to encompass the estimated area included in the impact for a 2 oz bird slice, and it defines the outermost boundaries of the impact area The 2 oz bird slice resides over approximately 30% of the blade span and the impact zone is defined by specifying a set of 3 D element faces In this case, 28 pressure faces were defined Also specified is the density of the bird (0 037 lb/m/in^3) and information defining the center chord line of the impact area and the pressure grid spacing to be used In this case, the center chord line is defined by nodes 139 and 167 and there are 40 pressure nodes (defined at the corners of each element face) It should be emphasized that the designated impact zone bounds the projected area of impact The actual projected area of impact will, in general, be smaller than the designated impact zone and is calculated and tracked by internal programming As mentioned previously, the pressures calculated by NOSAPM at the pressure grid points include the effects of the current blade geometry and structural velocities After the pressures are calculated at the pressure grid point locations, the pressures at the corners of the structural elements are used to calculate equivalent nodal loads based upon the deformed geometry of the element and under the assumption of a linear pressure distribution over each element face Figure 10 shows the bird loading pressure at three times during the impact Figure 11 shows the deformed geometry at 1010 μs and also, a comparison of the NOSAPM predictions with the results obtained from high speed movie analysis of blade leading edge displacements along the span It will be noted that a 2 oz strike is a relatively mild impact for this particular blade and the strain levels produced are significantly below those required to cause mass loss However, the blade did experience large displacements (in excess of 1 in) and the comparison of the predicted and measured displacements shown in Fig 11 shows excellent agreement, demonstrating the ability of NOSAPM to predict the impact response of a rotating blade Inspection of the blade after the test did not reveal discernible permanent deformation

Figure 12 shows a model used to simulate a nonrotating bench impact test on an instrumented blade like Titanium 8 AL 1Mo 1V structural specimen with a wedge shaped cross section This impact test was performed by Bertke[10] at the University of Dayton Research Institute For this impact test a compressed air gun was used to launch a 4 2 oz microballoon gelatin cylindrical projectile which impacted 29% of the target in the span direction Figure 12 shows the locations of the high frequency response strain gages that were used to obtain strain time histories

The NOSAPM analysis was accomplished in two solution segments (one restart) using the Newmark time integration method as follows: first segment, $0 \rightarrow 1280\ \mu s$; second segment, $1280\ \mu s \rightarrow 2560\ \mu s$ The time step size was equal to 10 $\times 10^{6}$ s which means that a total of 256 time steps were used in the analysis A fully geometric and material nonlinear

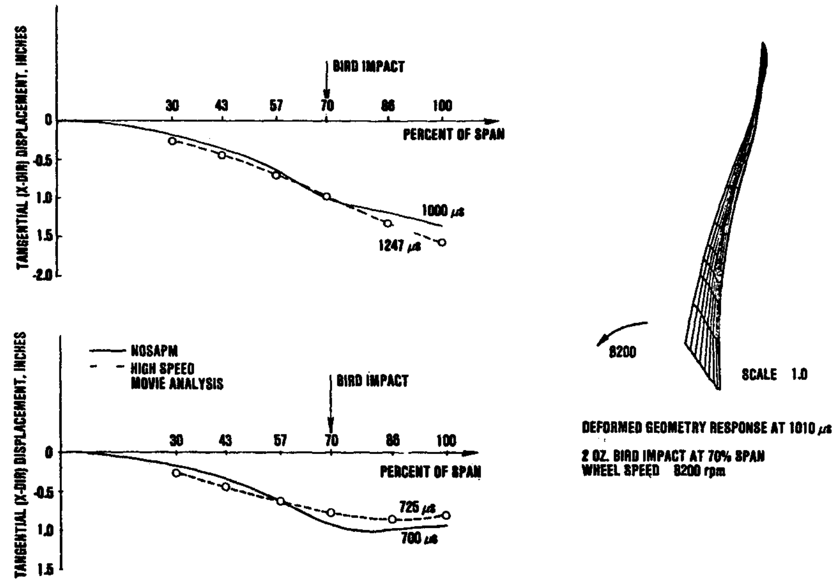

Fig 11 NOSAPM predictions and comparisons with test data for whirligig impact test

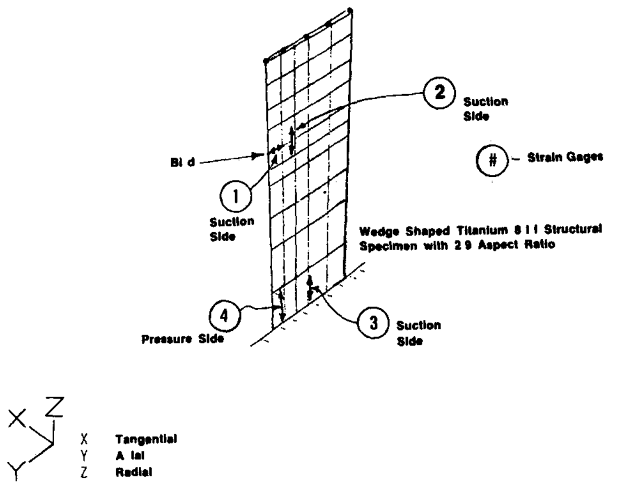

Fig 12 50 element model for simulation of static impact test, 4 2 oz bird at 70% span; impact velocity = 428 ft/s; incidence angle θ = 24 4 deg

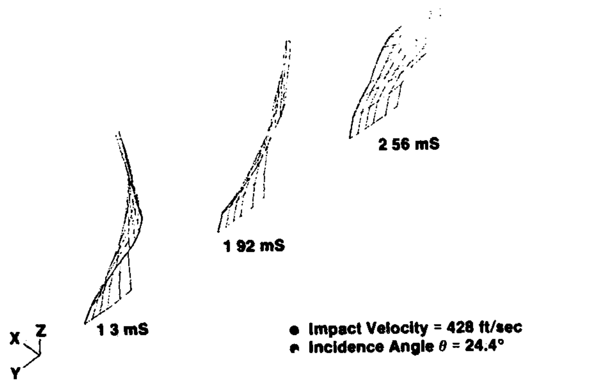

Fig 13 Distorted geometry for static impact test simulation, 4 2 oz bird at 70% span; impact velocity = 428 ft/s; incidence angle θ = 24 4 deg

impact analysis with stiffness matrix reformation for each time step was conducted, and the following material properties, obtained from Ref 11, were used

E_I = 17 3 × 10⁶ psi

E_2 = 139,000 psi

σ_{YP} = dynamic yield point stress = 164,000 psi

μ = 0 279

ρ = 0 15687 lb/in³

The distorted geometry is shown at 1300, 1920, and 2560 μs in Fig 13 Figure 14 shows the predicted and measured strains The agreement between the predictions and measurements is considered good and this case demonstrates the ability of NOSAPM to accurately predict the strains resulting from bird impact on a static blade

The full stage bird slicing model was used to analyze a 7 2 oz bird impact on a full stage of tip shrouded fan blades This test was not conducted as part of the FOD program effort, but was part of a component testing program consisting of impact tests with a whirligig rig configured from a full-scale fan rotor assembly and engine frame hardware For this test, high pressure helium was used to propel a real bird and the absolute axial velocity of the bird in the plane of the fan was 300 ft/s The angular speed of the fan was 7500 rpm The bird/blade interactive geometry representation used to model the impact is shown in Fig 1 In this case, the bird slicing model computes the size of the bird slice (2 46 oz residing over 16% of the blade span) that interacts with the blade and uses the bird's axial velocity and the blade's tangential velocity to compute the relative impact velocity (1276 ft/s) This approach differs from the single rotating blade analysis where the slice is predefined to agree with the known slice impacted to the blade by the injector mechanism in the whirligig facility, or with the known bird size for the bench testing Figure 15 shows that the primary damage was inflicted upon a single blade Its leading edge was curled back extensively and it exhibited a chordwise tear The NOSAPM model of the blade used to simulate the full stage impact is shown in Fig 16. The analysis was accomplished through the impact analysis of this single rotating blade model The model was fixed at the root nodes in the X, Y, Z directions and constrained at the tip nodes in the X and Y directions to represent the effects of the tip shroud interconnections Thus, the forces normal to the contact surface at the tip shroud, which represent the major interactive mechanism between the blades in the stage, are modeled with pinned boundary conditions in the tangential and axial directions This is justified because the tip shroud behaves basically as a hard spot, at least in the impact time frame needed to cause local damage (bulging, curl-back, and tearing in the impact region)

A fully nonlinear analysis, including the effects of centrifugal stiffening, was conducted out to 340 μs using the Newmark time integration method with a time step size equal

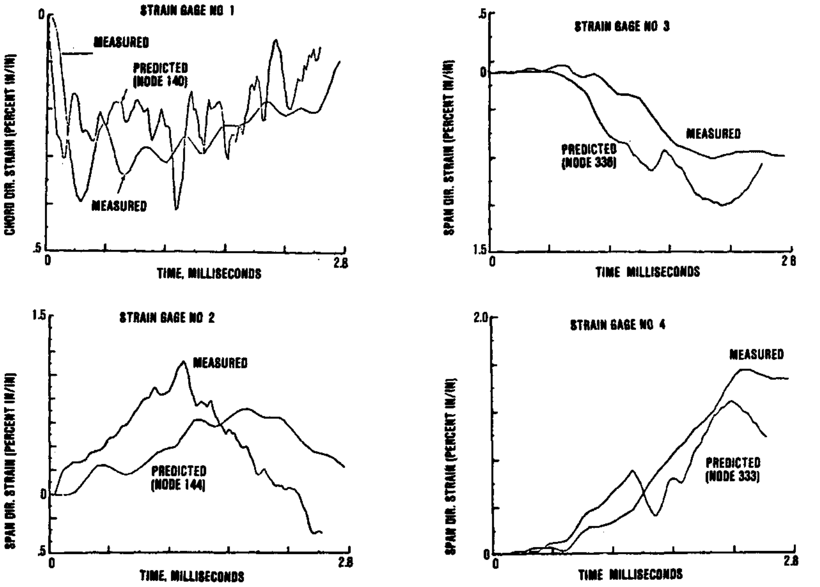

Fig 14 Comparison of predicted and measured strains static impact test, 4 2 oz bird at 70% span; impact velocity = 428 ft/s; incidence angle θ = 24 4 deg

Fig 15 Fan component testing blade damage from 7 2 oz dove at 70%

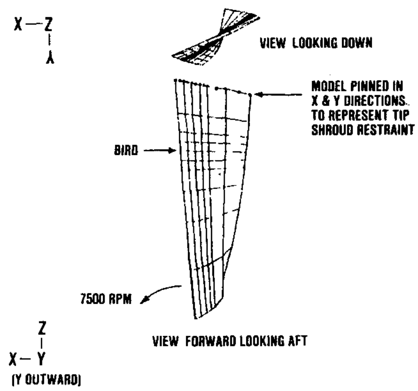

Fig 16 Full stage impact simulation 60 element NOSAPM model (7 2 oz bird at 300 ft/s, wheel speed = 7500 rpm)

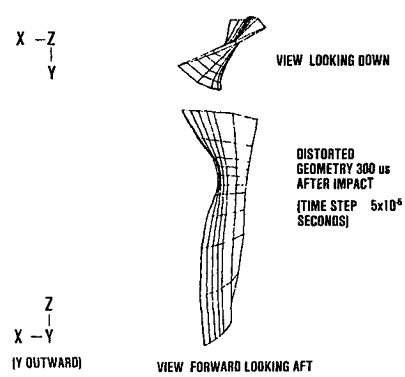

Fig 17 Full stage impact simulation 60 element NOSAPM model (7 2 oz bird at 70% span at 300 ft/s, wheel speed = 7500 rpm)

to 5×10^{6} s (68 time steps) The cost of the analysis on the CDC7600 computer was $500 This analysis had been initially performed with a time step size of 10×10^{6} s, but the local damage characteristics associated with the relatively large bird size and the effects of the shroud restraint necessitated a smaller time step, as evidenced by the abrupt transitions in the computed strain time histories The strain curves computed with the smaller time step were smooth in appearance and the peak value was increased by 28% over that calculated with the larger time step The 10×10^{6} s time step was based on characteristic time values derived from natural frequency and stress wave velocity calculations for a flat plate equal in size to the impact region Similar calculations, performed to estimate the time step requirements for the other impact cases presented herein, also indicated that a time step of 10×10^{6} s would be appropriate However, these cases did not demonstrate the local damage associated with the full stage impact and, consequently, the larger time step provided good results

The material for the blade is Titanium 8AL 1Mo 1V and the following material properties obtained from Ref 11 were used in the analysis

E_1 = 17 3 × 10^6 psi
E_2 = 139,000 psi
σ_{YP} = dynamic yield point stress = 190,000 psi
μ = 0 279
ρ = 0 15687 lb/in ^{3}

The distorted geometry is shown in Fig 17 The peak strains occur on the suction side at the leading edge, 74% span location and Fig 18 shows the time histories of the principal strains at this site As indicated in Fig 18, damage (tearing) will occur at 126 μs and this is based on the forming limit

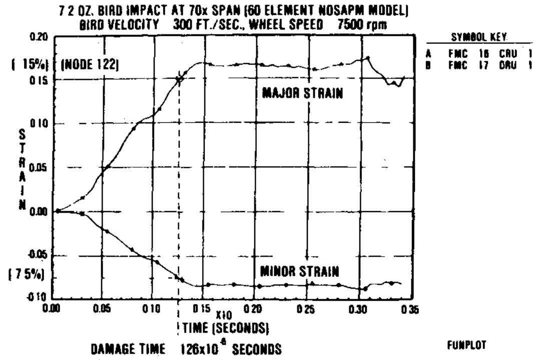

Fig 18 Full stage impact simulation, suction side principal strains at L E 74% span location

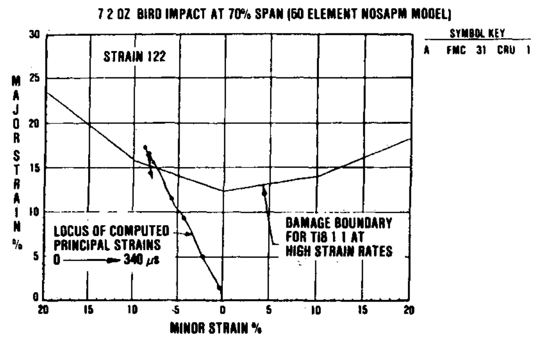

Fig 19 Full stage impact simulation, suction side principal strains at L E 74% span location compared to strain damage boundary (7 2-oz bird impact at 70% span at 300 ft/s, wheel speed = 7500 rpm)

diagram and principal strain locus plots shown on Fig 19 Thus, tearing and local distortion (curl back) are predicted in the impact region and this agrees with the test results This demonstrates the ability of NOSAPM and the damage criteria to predict local damage resulting from bird impact on a rotating blade

Conclusions

An impact response tool and design criteria have been developed which address both geometric and material nonlinearities as well as the load response interaction between projectile and rotating or stationary blades in turbine engines The transient structural response analysis is carried out with a three dimensional finite element program, a modified and extended version of the NONSAP code The interactive impact pressure calculations are based on potential flow theory and include the effects of detailed interaction between the loading model and the structural response of the target Design criteria have been developed which utilize the nonlinear analysis capabilities of the NOSAPM code and this includes a damage model which uses the time dependent performance of the material properties to predict tearing and possible mass loss The ability of the coupled nonlinear finite element code loading model, and damage criteria to predict nonlinear response and damage due to bird ingestion has been established with comparison to experimental impact data for both rotating and stationary blades

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