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Bird Impact Analysis Package For Turbine Engine Fan Blades

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BIRD IMPACT ANALYSIS PACKAGE FOR TURBINE ENGINE FAN BLADES

by

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ABSTRACT

A computer program has been developed to analyze the gross structural response of turbine engine fan blades subjected to bird strikes. The program couples a NASTRAN finite element model and modal analysis of a fan blade with a multi-mode bird impact analysis computer program. The impact analysis uses the NASTRAN blade model and a fluid jet model of the bird to interactively calculate blade loading during a bird strike event. The analysis package is computationaly efficient, easy to use and provides a comprehensive history of the gross structural blade response. Example cases are presented for a representative fan blade.

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INTRODUCTION

A significant factor to be considered during the design of an aircraft gas turbine engine is to provide adequate foreign object damage (FOD) tolerance. The specific component in a modern engine which is first struck by an ingested object, and which absorbs most of the impact, is the fan stage. Of those objects which are ingested, reasonably often, including small rocks, hailstones, and scattered debris, the most damaging is probably a medium to large size bird. Though the damage from hard objects can be severe, the objects themselves tend to be small compared to the blade, and the damaged area also tends to be small. Often this damage is discovered only upon ground inspection of the engine. On the other hand, birds can be relatively large, up to a few pounds, with a comparatively large impact area. Along with severe local damage near the leading edge of the blade, bird strikes can also produce loading near the root of the blade great enough to cause the blade (or blades) to break free.

The analysis of bird impact has received considerable attention. Investigations such as in reference 1 and 2 are concerned with fan blades directly, while much additional related information applicable to the analysis of fan blades has come from studies of canopy damage to military aircraft as a result of bird strikes[3,4]. In all cases, the problem of fan blade damage from a bird strike, in general, can be divided into two parts: (1) The prediction of severe local damage near the leading edge of the blade; and (2) the prediction of the overall blade response. Both parts of the analysis can require a significant amount of computer time.

The analysis package described in this paper provides an effective and efficient means for analyzing the overall response of fan blades to bird strikes. The package is composed of two key elements: (1) A modal analysis of the fan blade; and (2) an interactive bird strike analysis computer code. The modal analysis for this package is generated by NASTRAN. The bird strike analysis is based on a modified form of a computer code (Interactive Multi-Mode Blade Impact Analysis, MMBI) developed under contract for NASA[5]. This code uses a fluid jet model for the bird and models the dynamics of the fan blade from a supplied geometric description and modal analysis. As the bird impacts the blade the pressure loading during a given time step is calculated and decomposed into modal components. This loading is then used to numerically intergrate the modal equations of motion over a time step. One of the key features of the analysis package is that the NASTRAN finite element model and modal analysis are automatically integrated into the bird strike analysis code. The details of the MMBI code are presented in reference 5 and the fluid jet model of the bird is addressed specifically in reference 6. A detailed description and user's instructions are presented in reference 7. The purpose of this paper is to describe the integrated impact analysis package and present examples demonstrating its use. The MMBI analysis, in general, and the fluid jet model of the bird, in particular, will be described briefly in the next section.

ANALYSIS AND DISCUSSION

Analytical Models

A bird impact on a fan blade is depicted in figure 1. The bird first strikes the leading edge pressure side of the blade and begins to flatten. The bird continues to spread across the blade and after fully impacting slides off the blade. Note that if the bird is sufficiently large only part of the bird may actually impinge upon the blade. The bird is usually sliced by the blade and the rear portion of the bird may pass behind the blade without hitting it. In the MMBI analysis the pressure loading on the impacted surface of the blade is determined by modeling the bird as a composite of 2-D and 3-D fluid jets as shown in figure 2. As the impacting portion of the bird spreads over the blade the leading and trailing parts are modeled by a 2-D oblique impinging fluid jet. The sides are modeled by halves of a 3-D circular impinging jet. As the impact progresses with time, the newly impacted portion of the bird expands as a ring while the next portion impacts on the blade. If the bird impacts completely it continues to expand as a series of concentric rings.

Within the MMBI program the bird is represented by a discrete series of up to 6 segments as shown in figure 3. For the purposes of calculating the extent of the pressure loading, the blade is modeled as a flat plate with an embedded grid. The pressure loading is calculated at the grid points. The effects of blade motion and blade shape on impact angle, impact velocity and contact points are incorporated into the bird-blade interactions by assuming the bird moves along the deflected blade camberline at the impacted radius. The loading due to centrifugal force as a result of the bird sliding along the curved surface of a cambered blade is added to the pressure loading at the nodes.

In order to model the blade, two regions must be considered in detail: (1) The spanwise segment of the blade covered by the spreading jet model; and (2) the region near the root where critical stress data is desired. Since the motion of the blade is determined from modal synthesis this is sufficient blade data to obtain the gross response of the blade. Thus, only those nodes in the finite element model likely to be loaded, and those nodes not in this region where stress data is desired need to be identified. Displacement data is only printed for the leading and trailing edge nodes plus one column of interior nodes and the entire impacted chord. Thus, to obtain printed tip deflections nodes at the blade tip should be entered. As will be discussed later, data for easily generating the entire blade response is readily available, though not automatically printed. The advantage of not using the complete NASTRAN blade model is in reducing the overall problem size and thereby reducing the computation time and the volume of the output.

Coupled Analysis

The basic data needed by the analysis are the set of selected normal nodes, the flat plate blade description, the discrete bird model, the undeformed coordinates of the impacted camberline and certain physical and geometric orientation parmeters, including time-step size. Also, a modal stress vector is required for each normal mode vector. For the most general case all of this data must be supplied by the user. However, within the integrated analysis package, the NASTRAN and MMBI programs have been coupled through pre- and post- processors. Also, the MMBI program has been modified to provide more useful and comprehensive data. The coupled system flow chart is shown in figure 4.

The first step in the coupled analysis is to prepare a NASTRAN model of the blade and obtain the desired mode shapes and frequencies; up to 10 modes are currently allowed. This data is created once for each blade to be studied and is stored in a data file. Next the data is transformed by a post-processor into a form acceptable to the modified MMBI program. A single data card is required by this post-processor supplying only basic data such as, the number of nodes and elements and data file unit numbers. Currently, triangular and quadrilateral NASTRAN plate elements may be used. The post-processors must be called only once for each blade. The processed data set can be stored in a new file or rewritten over the old file to save space.

Each time an impact analysis is run the pre-processor is called to create a proper input data file for the modified MMBI program and to execute the impact analysis. The pre-processor appears as a subroutine within the modified impact analysis program and greatly reduces the user supplied data. Specifically, for each impact analysis the bird and the blade must be modeled discretely. A unique model for the bird may be specified or a pre-set, 6-slice spherical model may be used as shown in figure 3. In the latter case, the only required data is the diameter of the sphere. Optionally, a spherically capped cylinder may be created by specifying a distance between the hemispheres in the direction of motion.

Part of the function of the pre-processor is to create the flat plate representation of the blade. For cambered and twisted fan blades the two dimensional flat plate model cannot reproduce the blade planform geometry exactly. Because of the double curvature some geometric distorsion is unavoidable. However, the effects on the calculated pressure distribution should be very small for typical fan blade designs. The only data needed to create this model is the location of the blade stacking axis along each row of nodes in the impact model. Procedures within the analysis package will automatically form the flat plate model. The arc length of each row of nodes is first calculated, then the "straightened" rows are positioned as to preserve the location of the stacking axis along each row.

Two methods are provided for selecting the nodes in the NASTRAN model for use in the impact analysis. In the first case, the leading edge node for each row of nodes is identified followed by the remaining selected nodes in that row. The identifiers are the grid numbers in the NASTRAN model. The second case is a more powerful and compact method, but it is also somewhat more complex and will only be discussed briefly. The selected grid points are identified in an algorithmic manner. This method is most useful when more than a few nodes are involved, and when the NASTRAN grid points are distributed in sets of rows which have the same number of grid points.

For the NASTRAN plate elements typically used to model a fan blade, and currently allowed within the automated impact model generator, the stresses are given at the centroid of the element and are given relative to a local coordinate system in each element. For consistency within the analysis package the stresses are all transformed into local coordinate systems which all have their in-plane axes directed along the blade span and along the blade chord. The element centroidal stresses surrounding a node, are then weighted to generate nodal stresses.

Analytical Data and Model Refinement

The primary printed output data consists of the nodal stresses; displacements of leading edge, trailing edge and one interior node for each row of nodes in the impact model; plus the deflection of the entire impacted chord and the nodal loading due to pressure forces. Within the impacting region, as shown in figure 2, the total pressure force is numerically integrated and distributed between the two nodes closest to the center of pressure along the impact camberline. In the expanding rings the pressure force on each node is determined by the pressure at the node multiplied by a reference area as shown in figure 5. The area is rectangular and is equidistant between adjacent chordwise nodes and equidistant between adjacent rows of nodes.

For a coarse mesh this area may be too large to accurately compute the pressure forces of the nodes. As such, an option has been added to remesh a region above and below the impact station, as shown in figure 5. The remeshed region will have a uniform square grid pattern. The only data required by this option are the grid spacing, the number of rows to be generated above and below the impact radius and the chordwise extent of the remeshed region. The pressures will be computed at the nodes in the new grid. The total pressure force at these nodes is part of the printed output, but to integrate the response of the blade the forces are rewritten in the original grid. The force of each of the original grid points is determined from the pressures in the remeshed grid and the area in this grid enclosed by the effective area of the original nodes. This is shown in figure 5. The remeshing option is only necessary when there is the possibility that the forces on nodes within the expanding rings are significant and will be inaccurately computed due to a very coarse mesh. For shallow impact angles most of the pressure loading is confined to the footprint region of the impacting portion of the bird and thus, remeshing is not necessary. For highly cambered blades were centrifugal forces may be significant remeshing may be necessary.

Two output options are available which provide data files for generating the animated displacement response of the impacted blade and for generating time histories of stresses of selected nodes. In the first case, the modal amplification factors and the elapsed time will be written onto a file after each time step. This information along with the normal nodes generated by NASTRAN can be readily used outside of this analysis package to animate the entire impact response. To exercise this option only a non-zero I/O unit number designating the data storage file must be specified. In the second case the stress state and the elapsed time at selected nodes are written onto a separate data file after each time step. This data can be used to screen the impact analysis and to generate time history plots of the chordwise, radial, or shear stress of any of these nodes. This data was used to generate the plots shown in the next section. Only the I/O unit number of the storage data file and the identified nodes for which stress data is to be stored must be specified for this option.

EXAMPLES

Bird and Fan Blade Models

The examples given in this section illustrate the use and usefulness of the impact analysis package. All of the data given is for the same fan blade, analyzed for a number of different impact conditions and analytical models. The fan blade is shown in figure 6. It is a proposed shroudless, hollow all-titanium fan blade. The hollow portion of the blade is shown in this figure as are internal reinforcing ribs running the length of the hollow cavity. The blade dimensions are given in Table I. The NASTRAN model of this blade is shown in figure 7. The model consists of 423 nodes forming 777 triangular blade elements. The reinforcing ribs are represented by the narrow bands of elements running the length of the hollow portion of the blades.

The blade model shown in figure 7 was actually generated by a composite blade modeling computer program, COBSTRAN, developed by NASA[8]. This program is designed to create a NASTRAN model of a multi-layered blade as a single-layered model which has the same structural properties as the multi-layered blade. Each finite element is modeled individually so the construction of the blade does not have to be uniform. The advantage of this approach, as can be seen in figure 7, is that over the hollow portion of the blade both walls and the empty space between them are modeled by a single plate element. In order to do this with COBSTRAN the hollow cavaties were modeled by an artificial material defined as having negligible structural properties compared to titanium.

The first 6 natural modes of this model were used to describe the dynamics of the fan blade. The modal frequencies are given in Table 2. These frequencies include the influence of centrifugal force stiffening at 4000 RPM.

As discussed earlier, only a selected set of nodes is needed for the impact analysis. Specifically, this set must include those nodes likely to be directly loaded during the impact event plus any other nodes for which stress data or displacement data is desired. The nodes selected for all cases presented in this paper are shown in figure 8. As can be seen, relatively few of the 423 nodes are actually needed for this analysis. The impacted row is centered in the region of impact. Also, for all cases the bird is represented by a 6-slice model of a spherical missile as shown in figure 9. The discrete missile model is 3.75 in. long and weighs 1.0 lb. It is shown striking the camberline of the impacted radius of the blade. In all cases the impact angle was 25°. The missile model was generated automatically by the analysis package. The contact point between the spherical missile and the blade can be specified in one of two ways: (1) by giving the interception point of the projected missile camberline with the blade, or (2) indicating a relative initial contact point in terms of a distance between two nodes. The former is indicated by the coordinates (Xo, Yo) in figure 9, while the latter is shown by point a.

Analytical Results

Figure 10 shows the magnitude of the predicted leading edge deflection of the impact radius for 3 different impact velocities. Realistically, each impact velocity would result from a different engine speed, requiring that the mode shapes and frequencies be recomputed for each case. However, for illustrative purposes the modal data corresponding to an engine speed of 4000 RPM was used in all three cases.

As can be seen from this figure the early deflection histories are similar in shape. Also, the peak amplitudes occur at about the same time and, essentially, are scaled with respect to impact velocity. An interesting feature of the responses is that the displacement at the end of the impact contact time is about the same in all three cases, approximately 2 in. As such, the effect of blade motion and deflection on the total delivered impulse appears to be about the same for all three impact velocities. The calculated total impulses for the 600, 900, and 1200 ft/sec. impacts are .89, 1.33, and 1.78 lb-sec. respectively, which are essentially in the same proportion as the peak displacements.

The radial stress response for a point near the root is shown in figures 11 and 12 for impact velocities of 600 ft/sec. and 1200 ft/sec., respectively. The reference point is about an inch above the root of the blade and an inch behind the stacking axis. It is indicated by an "X" in figure 8. Both profiles are nearly identical and the peak stresses are again, essentially in proportion to the impact velocity, or correspondingly the imparted impulse. The radial stress response for an impact velocity of 900 ft/sec. also follows this trend.

Figure 13 shows the displacement response for blade models using 3, 4, and 6 modes for a 1200 ft/sec. impact. As can be seen, the peak responses are very close though the latter portions of the response curve differ somewhat. Figures 14 and 15 show the corresponding radial stress response of the reference point for a 3 mode and 4 mode blade model, respectively. From these figures it can be seen that the 4 mode blade model predicts essentially the same stress response as does the full 6-mode model, while the 3-mode model predicts significantly lower stress levels. Thus, for the impact events analyzed, a 4 mode blade model would be adequate to predict both gross displacement and radial stress response.

By using the analysis package described in this paper the data for figures 11 through 15 were generated easily and efficiently. Since all 6 NASTRAN modes were originally post-processed along with the NASTRAN geometric model of the fan blade, all of the blade data required by the modified MMBI analysis program was stored on a data file. As such, the only change to impact analysis input data was to change two numbers: (1) the impact velocity, and (2) the number of modes used to model the blade.

The data was generated on a UNIVAC 1100/42 computer. Storage requirements for each case was approximately 60,000 words, and the CPU time required for each case was approximately 5 min. Had additional, rather then fewer, modes been needed to model the blade, they could have been appended to the existing file of NASTRAN modeling data. This file would then have to be re-processed to form a new permanent data base for the impact analysis program. However, this processing requires only about 1 min. of CPU time on the UNIVAC 1100/42 computer.

As discussed previously the stress response curves were made from an optional auxillary output file and standard graphics software. The availability of the data in a form easily tied to a graphics device greatly increases the usefulness of the total analysis package. It is not always clear where or when the stresses of greatest interest occur. Typically, the peak stress levels of different points on the blade do not occur at the same time. In choosing the reference point for the data presented here the response of a number of points were first quickly surveyed using the data on the auxiliary data file. The reference point was chosen on the basis of being in a thick portion of the blade which carries most of the steady load, and on the basis of having a comparatively large peak stress.

Some of the additional data which is available to analyze an impact event is shown in figure 16. The total pressure force, total imparted impulse and the center of force along the camber line are plotted as a function of time for a 600 ft/sec. impact.

As can be seen the pressure builds quickly and then holds a relatively steady value for most of the duration of the impact. This is a result of the fluid jet model of the bird. The irregularities in the pressure profile are due to the discrete 6-slice model of the bird. An interesting feature of the top curve shown in this figure is that the center-of-force remains within about an inch of the leading edge for about the first third of the impact. This is due to two factors. First, the footprint of the impacting missile is building during the early stages of the impact. Thus, the impacted area of the blade is growing in size but not yet moving across the blade. Secondly, as shown in reference 5 and 6, for shallow impact angles, the center-of-force lies considerably behind the center of the impact footprint. In fact, during the entire impact event the center-of-force moves only to about mid-chord before the pressure loading vanishes. As a result, more than half of the impulse is delivered over the leading quarter chord of the blade. For large spherical bird models or long cylindrically shaped bird models the center-of-force will span a larger portion of the blade chord. One advantage of having this data and modeling the missile by discrete slices is that the analyist can tailor the missile model to approximate a desired or experimentally determined loading profile.

SUMMARY

The impact analysis package described in this paper combines NASTRAN with a modified version of an existing bird impact analysis computer program to provide a versatile and easy to use tool for analyzing the gross response of aircraft turbine engine fan blades to bird strikes. Additionally, the package is computationally inexpensive. The examples shown presented the type of data available within the analysis package and its usefulness in establishing an effective bird-blade model to be used to predict bird strike tolerance. The analysis predicted that for a range of impact velocities only four modes are needed to describe both the displacement and stress response of a particular fan blade to a bird strike. The range of impact conditions studied easily could have been extended to include such factors as the modeled shape of the impacting bird, the angle of impact and the initial contact point on the blade. One of the key features of the analysis package is the automatic incorporation of a NASTRAN geometric model and modal analysis to model the blade. This allows available realistic mode shapes to be used to dynamically model the blade without extensive effort on the part of the user.

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TABLE I

Fan Blade Description

Length	28 in
Aspect Ratio	2.4 in
Tip Radius	43.2 in
Tip Speed	1500 ft/sec
Weight	18.2 Lb
Impacted Radius	35.2 in
Impacted Chord Length	13.0 in

TABLE II

Natural Frequencies at 4000 RPM

Mode	Frequency (Hz)
1	112
2	216
3	271
4	394
5	466
6	545

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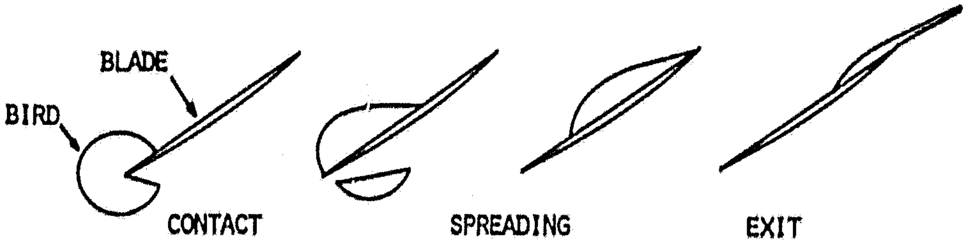

FIGURE 1 - IDEALIZED BIRD IMPACT

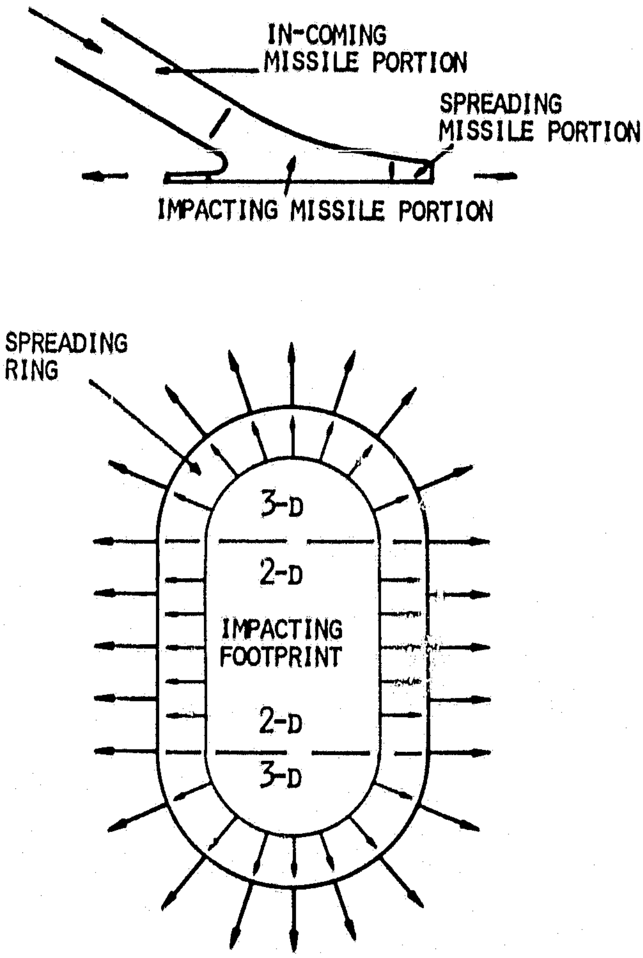

FIGURE 2 - FLUID JET MODEL

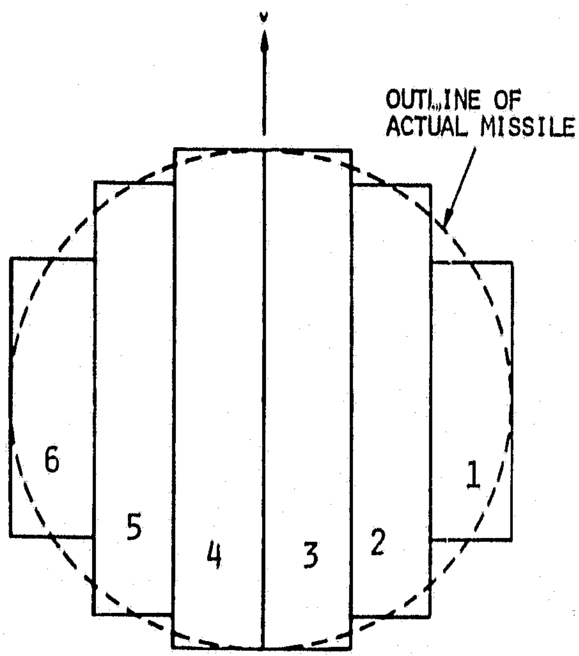

FIGURE 3 - DISCRETE MISSILE MODEL

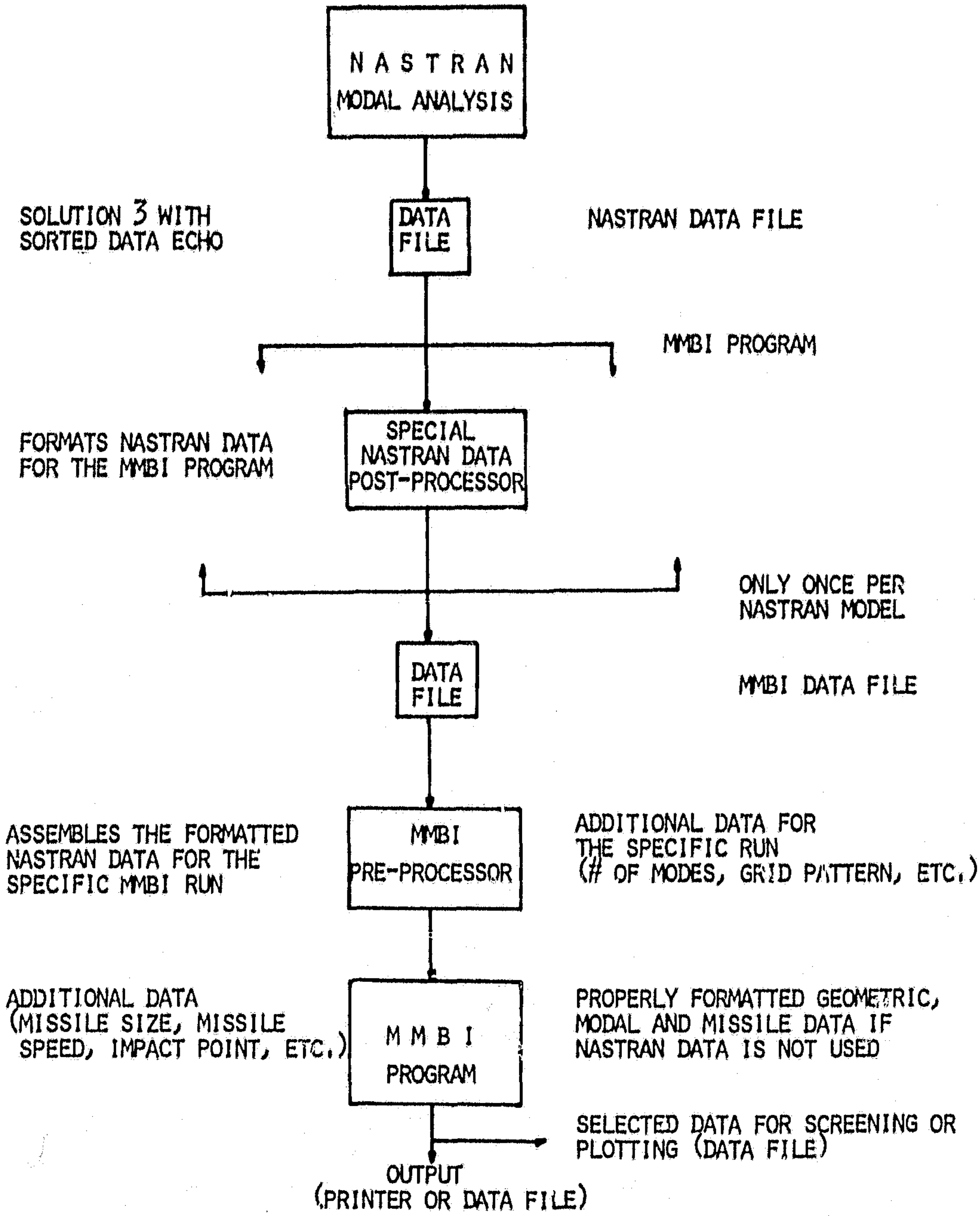

FIGURE 4 - IMPACT ANALYSIS FLOWCHART

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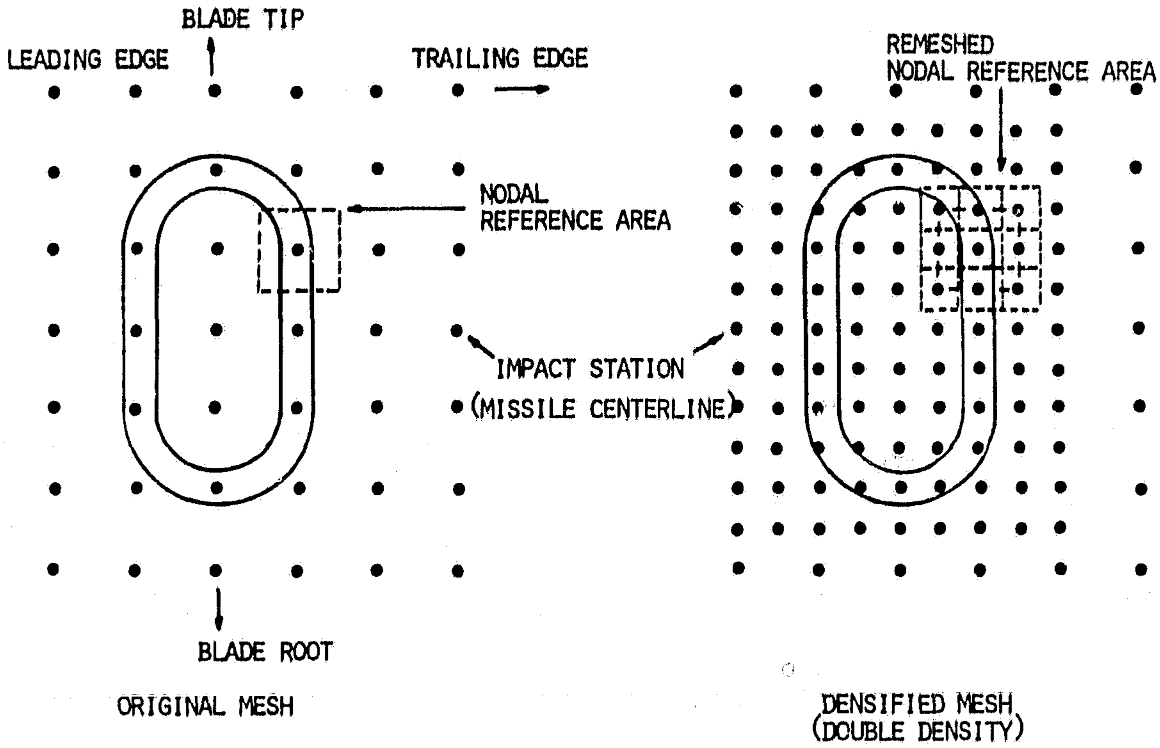

FIGURE 5 - IMPACT PRESSURE LOADING DISTRIBUTION

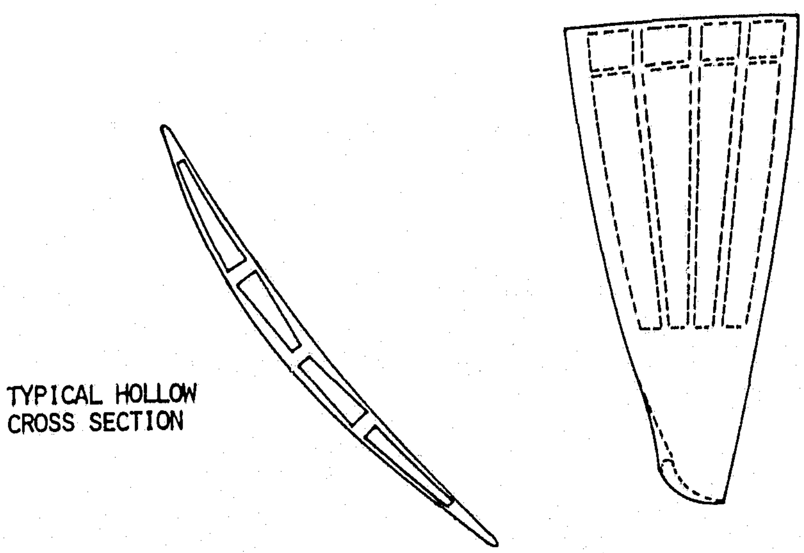

FIGURE 6 - HOLLOW FAN BLADE

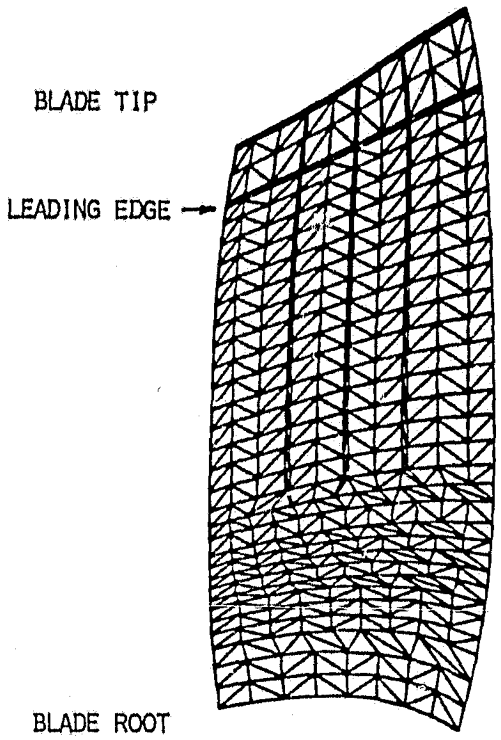

FIGURE 7 - NASTRAN BLADE MODEL

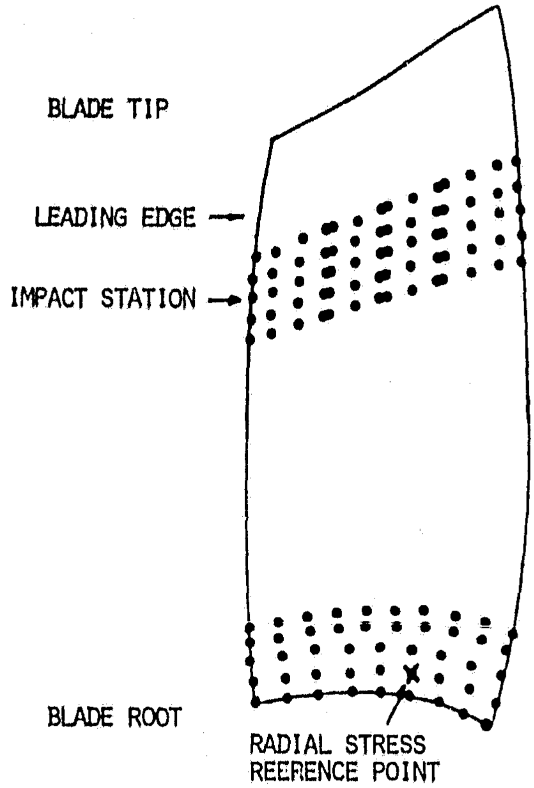

FIGURE 8 - SELECTED NODES FOR THE IMPACT ANALYSIS

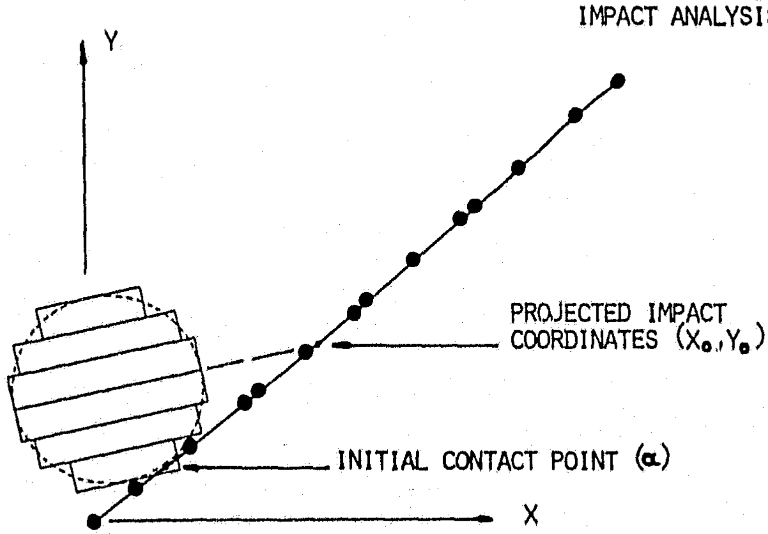

FIGURE 9 - SIMULATED BIRD STRIKE MODEL

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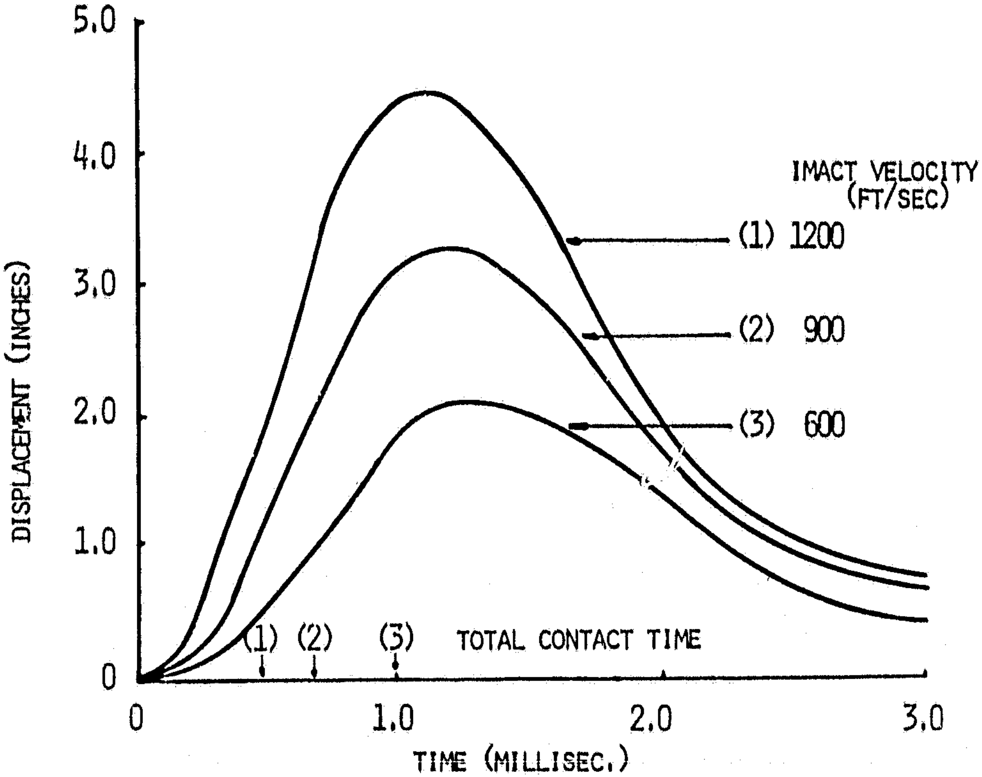

FIGURE 10 - MAGNITUDE OF THE LEADING EDGE DISPLACEMENT AT THE IMPACT STATION

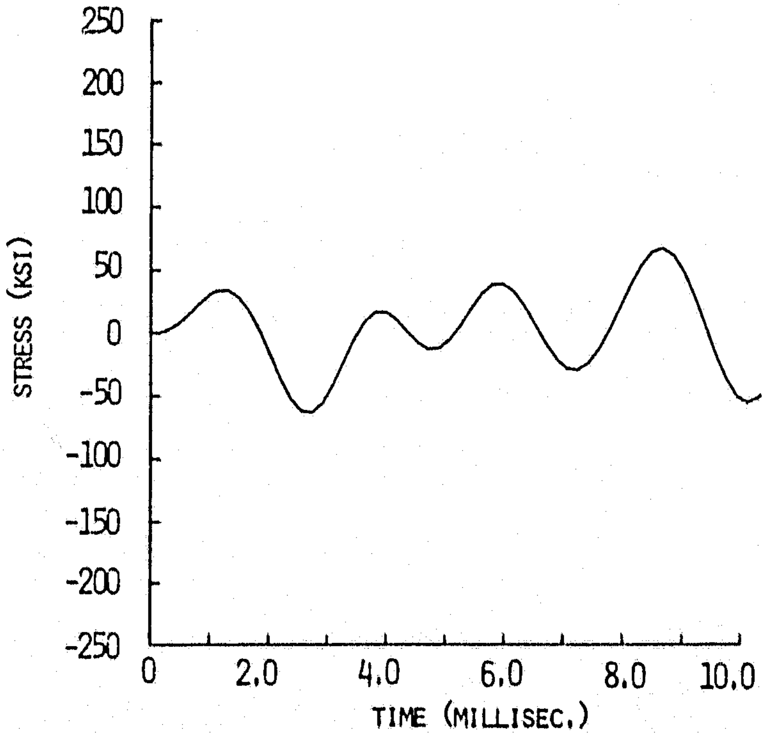

FIGURE 11 - RADIAL STRESS RESPONSE -- VELOCITY = 600 FT/SEC, 6 MODES

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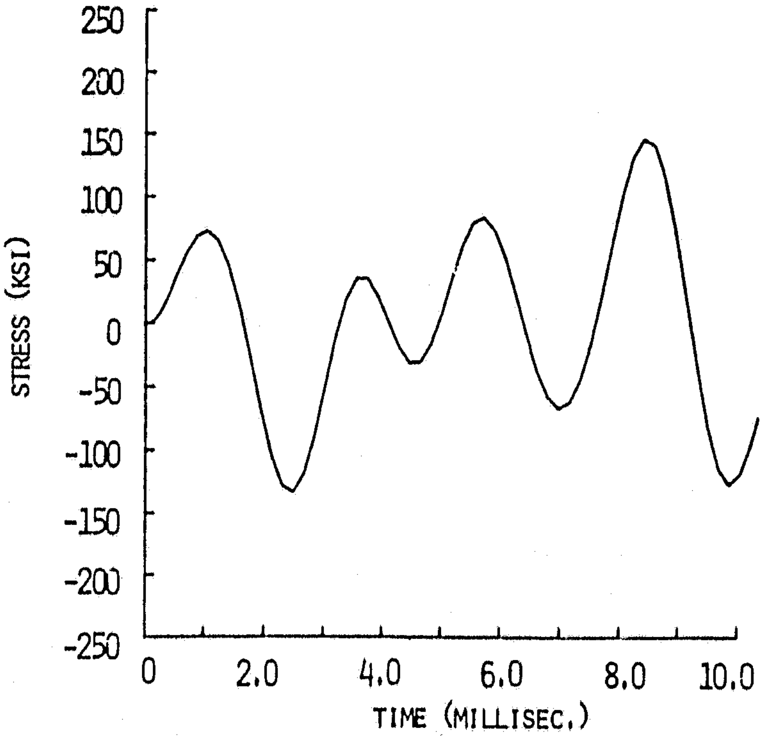

FIGURE 12 - RADIAL STRESS RESPONSE --
VELOCITY = 1200 FT/SEC, 6 MODES

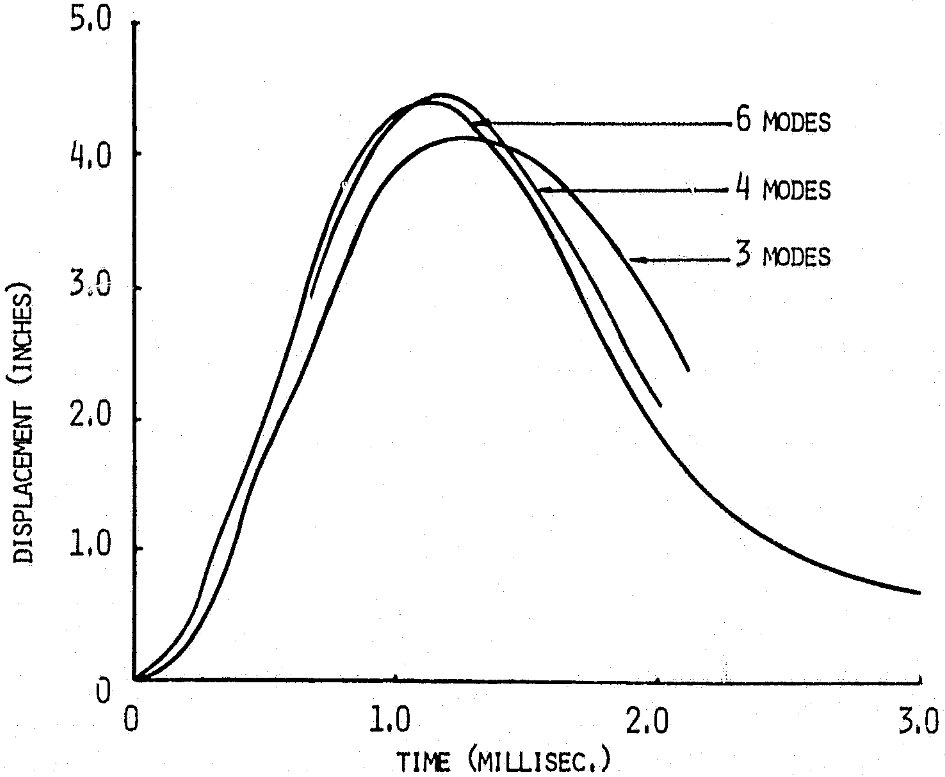

FIGURE 13 - EFFECT OF MODAL BLADE MODEL ON DISPLACEMENT RESPONSE

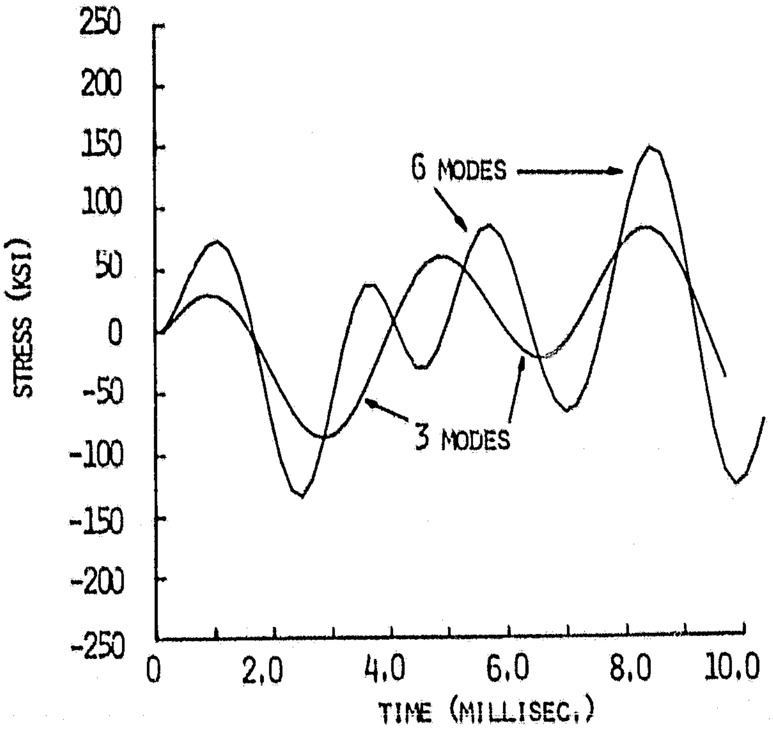

FIGURE 14 - RADIAL STRESS RESPONSE --
VELOCITY = 1200 FT/SEC, 3 MODES AND 6 MODES

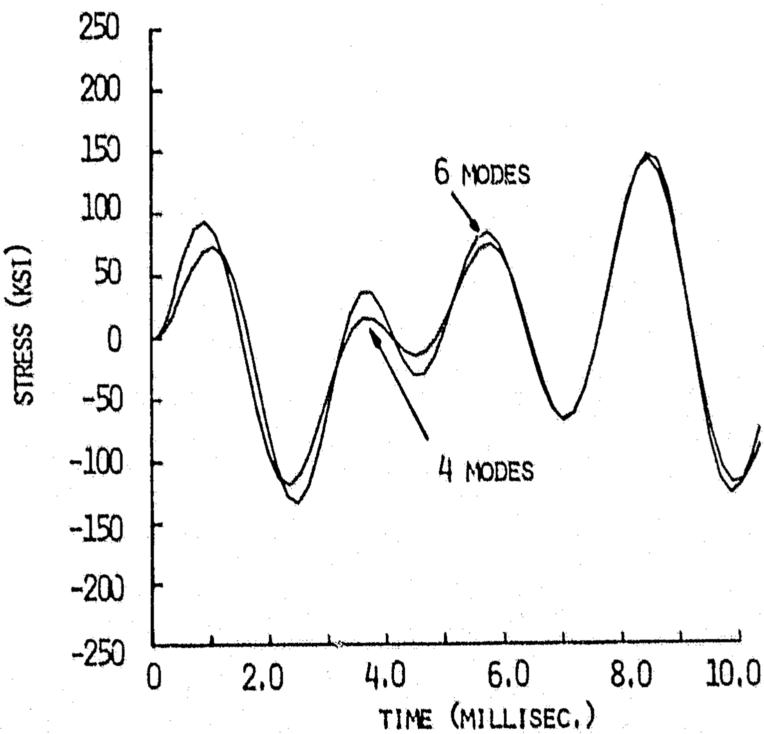

FIGURE 15 - RADIAL STRESS RESPONSE --
VELOCITY = 1200FT/SEC, 4 MODES AND 6 MODES

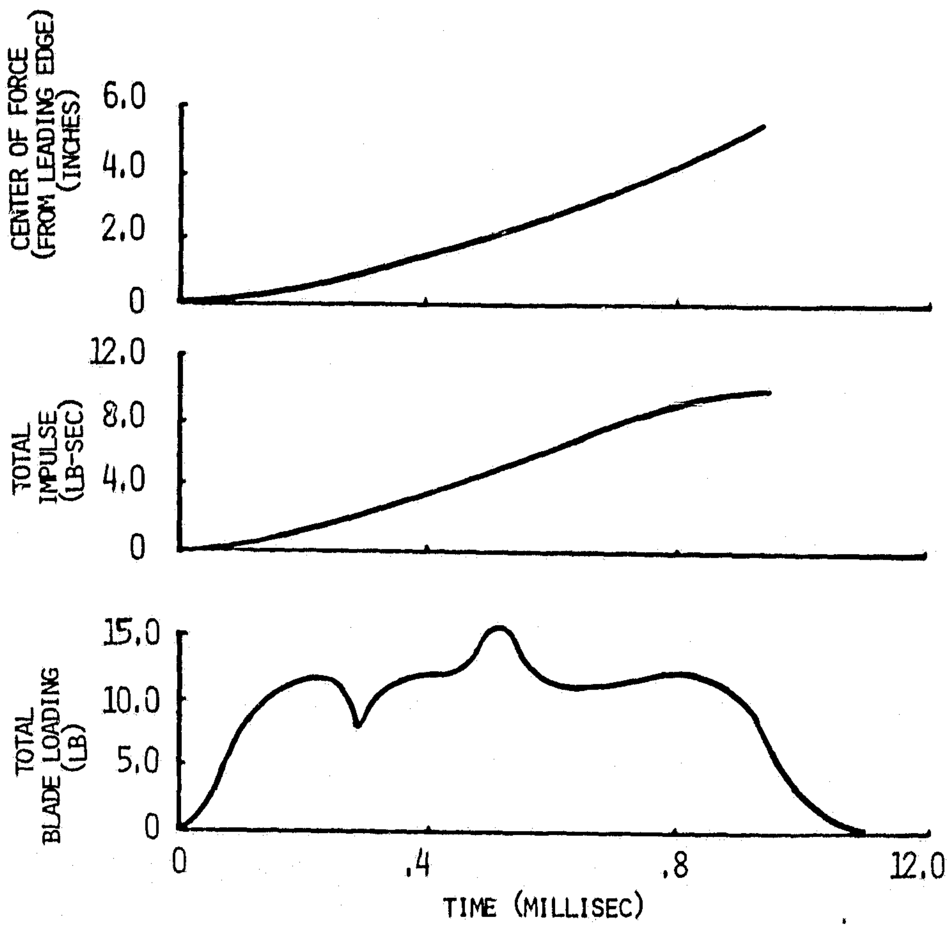

FIGURE 16 - IMPACT ANALYSIS DATA
VELOCITY = 600 FT/SEC