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TRANSIENT RESPONSE OF A CANTILEVERED PLATE TO IMPACT USING HOLOGRAPHIC INTERFEROMETRY AND FINITE ELEMENT TECHNIQUES

PROPULSION BRANCH TURBINE ENGINE DIVISION

AUGUST 1976

AFAPL-TR-76-56

TECHNICAL REPORT AFAPL-TR-76-56 FINAL REPORT FOR PERIOD 1 JANUARY 1976 TO 1 AUGUST 1976

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James C. Mr. Bain

DR. JAMES C. MACBAIN Project Engineer

FOR THE COMMANDER

GERSHON, Tech Area Manager

Fropulsion Branch Turbine Engine Division

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FOREWORD

This report covers work carried out at AFAPL's Turbo Structures Research Laboratory (TSRL) on the transient structural response of an isotropic cantilevered plate subjected to normal impact by a ballistic pendulum. The effort was intended as a vehicle for evaluating the methods of pulsed laser holography and finite element analysis as they relate to the study of transient structural dynamics. This is an area which bears directly on the problem of foreign object damage to turbine engine components.

The program was a combined expermental/analytical effort. The experimental portion utilized a pulsed ruby laser to obtain holographic interferograms of the plate's deformation following impact. The analytical portion of the work consisted of mathematically modelling the plate using finite element techniques and studying the model's response to impact using the general purpose finite element program, NASTRAN.

The work was performed in the Turbine Engine Division of the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio under Project 3066, Task 12, and Work Unit 21. The effort was conducted by Dr. James C. MacBain of the Propulsion Branch.

The author is indebted to Mr. Bruce Tavner for his very competent technical assistance in the laboratory and to Miss Helen Davis for typing the manuscript.

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SECTION I

INTRODUCTION

Foreign object damage in both military and civilian turbine engines is a seldom but serious problem both in terms of cost and safety. For example, the Air Force Inspection and Safety Center states that 2816 birdstrikes have been reported Air Force-wide between 1966 and 1973. These birdstrikes resulted in a loss of 7 lives, 14 aircraft, and a cost to the Air Force of \$74 million dollars. These figures serve to underline the fact that there is a definite need for both basic and applied research in the area of impacttolerant turbine engine blading. More sophisticated design tools and impact theories are required. In this vein, this report covers work carried out at AFAPL's Turbo Structures Research Laboratory (TSRL) on the transient structural response of an isotropic cantilevered plate subjected to normal impact by a ballistic pendulum. The program was a combined experimental/analytical effort. The experimental portion utilized a pulsed ruby laser to obtain holographic interferograms of the plate's deformation following impact. The analytical portion of the work consisted of mathematically modelling the plate using finite element techniques and studying the model's response to impact using the general purpose finite element program, NASTRAN.

The specific aims of this research effort were threefold. First, the advantages and disadvantages of using pulsed laser holography for transient structural analysis were studied. Second, it was intended

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to use the experimental pulsed holography results as a verification of results obtained analytically using the computer program, NASTRAN. Finally, the research effort served to provide knowledge of and experience with pulsed laser holography - information that will be useful in future TSRL research efforts.

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SECTION II SUMMARY OF RESULTS

An aluminum cantilevered plate measuring 3"x7"x.1875" was struck with a ballistic pendulum consisting of a .65" diameter steel ball attached to a wire on a pivot. The resulting plate response was measured for a specified time after impact by double exposure holographic interferometry using a pulsed ruby laser. The plate's normal displacement was experimentally determined for times after impact ranging from 2 to 33μ s. Photographs of the double exposure holograms from these tests are shown in Figures 4.1-4.5. The normal displacement based on four of the test runs (times after impact of 4, 6, 12, and 18μ s) is shown as a function of plate geometry in Figures 4.10-4.13.

The flexural wave velocity was computed from the holographic interferograms by plotting the plate wave position versus time after impact and was found to be $C_f = .102 \text{ in/}\mu \text{s}$. This is in good agreement with the theoretical Rayleigh surface wave velocity of .112 in/ μs - a difference of 8.5%.

A parallel numerical study was conducted using the finite element computer program NASTRAN to compute the cantilevered plate's transient response. The results were in good agreement with the experimental findings. The plate's normal displacement based on finite element analysis is shown plotted in Figures 4.10-4.13 as a function of plate geometry (dashed lines). Contour plots of the plate's normal displacement for different times after impact were also generated by NASTRAN and are shown in Figures 5.3-5.5.

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The study demonstrated the feasibility and utility of using pulsed laser holography to study transient structural response. In addition, it provided increased confidence and experience in the use of NASTRAN's transient analysis capability.

SECTION III

EXPERIMENTAL SET UP AND PROCEDURE

3.1 Physical Configuration

The test piece for the experimental portion of the impact analysis program was a 6061-T6 aluminum plate measuring 12" in length, 3" in width, and 3/16" thick. The plate was fixed between two steel blocks having a total weight of 33 lbf such that it was cantilevered and had a free length of 7". The weight of the cantilevered portion of the plate was .394 lbf. The plate and jig are shown in Figure 3.1.

The plate was impacted normally by a steel ball weighing .043 lbf at a point lying on its long axis and located 3" above its fixed end as shown in Figure 3.1. The ball was soldered to a thin wire that in turn was fixed to a pivot located a distance above the impact point forming what is known as a ballistic pendulum. The impact sequence was initiated by suspending the steel ball from an electromagnet which was then switched off allowing the ball to swing down and strike the plate. Just prior to impact, the ball interrupted a continuous wave laser beam passing behind the plate (see Figure 3.2) causing a photo diode to transmit a lOV signal that initiated the pulsed laser firing sequence. The timing and electronics involved in the pulsed laser firing sequence will be addressed in more detail in a later section.

The optical set up for making the hologram is also shown in Figure 3.2. The placement of the optics is typical of that used to make transmission holograms with an off-axis holographic set up, and the reader is referred

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Figure 3.1 - Cantilever Plate and Pendulum Geometry



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Figure 3.2 - Experimental Set-up for Making Holographic Interferograms

to Reference 1 for details. The holograms were made using a pulsed ruby laser (Apollo Model 22HD). The laser puts out 2.5 joules/pulse, 20-50ns in width, which necessitates the use of dielectric mirrors and doubly concaved lenses (F.L. = -40mm) when working with the unexpanded laser beam. While TSRL's pulse ruby laser is capable of rapid double pulsing down to pulse separations of lµs, this was not done in the present experiment. Because of timing constraints placed on the ruby laser (see Section 3.2), the holographic interferograms were made by first exposing the photographic plate to a single manually initiated laser pulse prior to impact and then again exposing the photographic plate some time, Δt , after impact. This second exposure was also done in the single pulse mode but in this case was triggered automatically. This will be discussed in greater detail in the next section.

3.2 Electronic Timing Circuitry for Firing Laser

When the ballistic pendulum impacts the cantilever plate, flexural waves spread out from the impact point at a velocity approaching the shear wave velocity, $C_s = \frac{G}{\rho}$, of the material (Ref. 2). For 6061-T6 aluminum, the flexural waves will have a phase velocity approaching .114 in/µs. This means that when the plate is impacted, the resulting flexural waves will only take about 16µs to travel the 1.5 inches to the free sides of plate. Now, one of the objectives of the present study was to analyze the plate deformation just after impact, i.e., at times after impact <u>prior</u> to significant wave reflection off the plate's boundaries. For acceptable results, this places an upper

bound on the time for firing the second laser pulse of about 30μ s (wave reflection will occur off the closest free edges of the plate at t = 16µs). This in turn places some constraints on the firing sequence for the ruby laser since, as shown in Figure 3.3, the ruby laser can fire only after 200µs have elapsed - the amount of time necessary for the flash lamps to energize. This is true for either the single pulse, as in the present case, or the double pulse mode of operation. Hence, in order for the laser to lase automatically at some time after impact in the 0-30µs range, it would have to be triggered (signal sent to Master Sync) at some time prior to impact. This was done using a timing delay oscilloscope (Tektronix 535) as follows.

Prior to making the double exposure hologram, the time that it took the ball to go from the trigger laser beam to the plate was measured by an electronic counter. This is shown as T_{AC} in Figure 3.4. This distance traversed by the ball in going from A to C was approximately 1 inch and T_{AC} was typically in the .02 second range (20,000µs). Upon specifying the time after plate impact to be observed, T_{IMPT} , and utilizing the fact that Pulse #2 of the laser fires at 1000µs into the firing sequence, the delay time, T_{AB} , was determined from the relationship:

$$T_{AB} = T_{AC} + T_{IMPT} - 1000 \mu s$$
 (3.1)

The delay oscilloscope was then set so that a signal was sent to trigger the ruby laser after a delay of T_{AB} seconds. The Pockels cell voltage for Pulse #1 of the ruby laser was set to zero, thus eliminating Pulse #1 from the firing sequence.



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Figure 3.4 - Impact/Laser Timing Sequence

With the steps mentioned above carried out, the actual impact test was run. First, the magnet was energized and the pendulum attached to it. The first exposure of the stationary cantilever plate was then made by manually firing the ruby laser (Pulse #2, only). The ruby laser then was energized again, the magnet was switched off, allowing the ballistic pendulum to swing down, interrupt the trigger laser beam (point A), initiate the ruby laser firing sequence (point B), and impact the plate (point C). At T_{TMPT} seconds after initial contact between the ball and plate, Pulse #2 of the ruby laser fired, exposing the photographic plate for the second time. During this impact sequence, the time T_{AC} was again measured as it varied somewhat between tests. Knowing the value of TAC for the actual test, the actual value of the time after impact, T_{IMPT} could be computed from equation (3.1). A schematic of the electronics used in the experiment is shown in Figure 3.5. A switch was put in the electronic counter portion of the circuit (located at bottom of Figure 3.5) in order to facilitate quick monitoring of the present scope delay time, TAB, or the time it took the ball to go from the trigger laser to the plate, T_{AC} .

3.3 Hologram Processing

21

The photographic plates used in the experiment were 4"x5" Agfa-Gevaert 10E75. The photo cell and storage oscilloscope shown behind the hologram in Figure 3.5 were used to measure the reference to object beam ratio and pulse amplitude of the holographic set up. The beam ratio for the tests was approximately 2 to 1 (reference beam to object beam). The combination of photo cell and storage oscilloscope could only give

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Figure 3.5 - Electronic Circuitry for Making a Double Exposure Hologram

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relative light intensity measurements, i.e., the amplitude of the reference beam relative to the object beam or the relative amplitude between the first and second plate exposures. This sufficed, however, for the present experiment. With the photo cell placed 1" behind the hologram plate holder, "acceptable" holograms resulted for oscilloscope readings of .4 volts and .6 volts with and without a photographic plate in the holder, respectively. The resulting holograms tended to be dark but this was corrected by bleaching the developed photographic plates. The developing process was carried out as follows:

1. 4 minutes in Kodak D-19 developer;

- 2. 30 seconds in stop bath;
- 3. 3 minutes in fixer;
- 4. Dry with blow dryer;

Bleach in Potasium Ferricynanide (15g of K₃Fe(CN)₆ in 1000 ml distilled water) - agitate until plate becomes milky white, approximately 1 minute.

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SECTION IV

EXPERIMENTAL DATA REDUCTION AND RESULTS

Figures 4.1 through 4.5 show the cantilevered plate's response for times after impact ranging from 2µs to 33µs. For the sake of increased fringe clarity, the photographs taken of the holograms show the immediate area of impact. Recall that the impact point lies on the vertical axis of the plate and 3 inches above the clamped base. The numbers in parentheses refer to the raw data numbering system used to denote each test run. The 6061-T6 aluminum plate was painted with a flat white paint and a grid having 1" by .5" increments was scribed on it. In addition, 1/8" increments were scribed on the plate centerline from the impact point to 1" below it.

Referring to Figures 4.1 through 4.5, the fringes concentrically located around the impact point (ball impacting from rear) represent loci of constant displacement on the plate. The fringes are a contour map of the flexural waves caused by the impact. They travel outward with time until they reach the free edge of the plate at about $T=12\mu$ s and are reflected. It is evident from the photographs that either the timing measurements are in error by as much as $\pm 2\mu$ s or that there was some scatter in the magnitude and duration of the impulse load imparted to the plate by the steel ball pendulum. The latter reason is thought to be the case because of a permanent magnetic field that











was induced in the electromagnet used to release the steel ball. The permanent magnetic field varied somewhat throughout the duration of the impact tests. The magnetic force field would have the effect of slowing up the ball's release and, consequently, decreasing its impact force. This fact is corroborated by Figures 4.6 and 4.7 where the force time profile is seen for four successive ball impacts on a pressure transducer (Piezotronics, PCB 118A-B, 2µs rise time) temporarily imbedded in the plate at the impact point. The pressure amplitude (proportional to force) in test 1 is 20% less than the tests 2 through 4. While future work in this area should strive for a more repeatable loading system, the present data scatter was found to be acceptable within the scope of the present research effort. The load profile shown in Figures 4.6 and 4.7 was also utilized to determine the loading input for the finite element analysis (Section 5.1).

The fringe pattern position and the corresponding times after impact in Figures 4.1-4.5 can be used to compute the velocity of the flexural waves in the plate. Using the outermost visible fringe for times after impact ranging from 2μ s to 13μ s, one can get a plot of wave position as a function of time. The slope of this curve will be the flexural wave velocity. Using the fringe pattern positions and corresponding times in Figures 4.1 through 4.3, the curve shown in Figure 4.8 was generated. Because of the aforementioned scatter due to load repeatability, a linear least squares routine was used to generate the curve through the data points. The slope of the curve gives the flexural wave velocity as $C_f = .1024$ in/µs.



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Figure 4.7 - Pressure Transducer Output at Impact Point Vs Time (Tests 3 and 4)



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Figure 4.8 - Flexural Wave Position As a Function of Time After Impact

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It is of interest to compare the experimental value of the flexural wave velocity to that obtained using the three-dimensional equations of elasticity (Ref. 2, 3, and 4). According to classical plate theory, the flexural wave velocity in an infinite plate approaches that of a Rayleigh surface wave when the wavelength, λ , becomes small compared with the plate thickness, h. In the case of the present impact tests, the steel ball made contact with the plate over a circular area of less than .03125 inches in diameter. Now, the wavelength, λ , is a function of the pulse shape and plate contact area, and if the pulse loading is broken into its Fourier components, the largest component's wavelength will be on the order of twice the diameter of the contact area. Hence, the smallest value of h/λ for the plate with h = .1875 is h/λ = 3. All other values of h/λ for the higher Fourier components will be greater than this value. For values of $h/\lambda > 3$, the flexural wave velocity in a plate closely approximates that of a Rayleigh surface wave and can be obtained from the expression (Ref. 4).

$$C_{f} = .932 C_{s} \qquad (v = 1/3) \qquad (4.1)$$

$$C_{s} = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2(1+v)\rho}} \qquad \text{is the shear wave velocity.}$$

For the test plate; $E = 1 \times 10^7$ psi, v = .3, and $\rho = 2.587 \times 10^{-4}$ lbm. Placing these values into equation (4.1) yields a value of $C_f = .112$ in/µs. This is within + 8.5% of the experimental value.

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The magnitude of the plate's displacement can be obtained from the fringe photographs using the expression (Ref. 5 and 6):

$$\delta \cdot (\vec{n}_{0} + \vec{n}_{v}) = \frac{(2N\mp1)\lambda}{2}, \text{ for } N = \pm 1, \pm 2, \pm 3 \ldots$$
 (4.2)

where $\overline{\delta}$ - displacement vector

- \vec{n}_{o} unit vector in direction from object to illumination source (object beam)
- \vec{n}_v unit vector in direction from viewer (through hologram) to object
- λ wavelength of laser used to make the hologram
- N fringe order

The vectors given by equation (4.2) are shown in the context of the present experimental geometry in Figure 4.9.

Carrying out the dot product in equation (4.2) yields:

$$|\vec{\delta}||\vec{n}_{0} + \vec{n}_{V}|\cos(\vec{n}_{0}, \vec{n}_{V}) = (2N \mp 1)\lambda$$
(4.3)

letting $|\vec{\delta}| \equiv \delta$ and using Figure 4.9 gives

$$|\vec{n}_{0} + \vec{n}_{v}| = |1.975 \vec{i} + .222 \vec{j}| = 1.987$$
 (4.4)

$$\cos{(n_o, n_v)} = .975$$
 (4.5)


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Hence, the displacement, $\delta,$ in the direction that bisects \vec{n}_{0} and \vec{n}_{v} is:

$$\delta = \frac{(2N \mp 1)\lambda}{(2)(.975)(1.987)} = \frac{(2N \mp 1)\lambda}{3.874}$$
(4.6)

The displacement normal (perpendicular) to the plate surface differs from that given in equation (4.5) by only $\cos\left(\frac{\dot{n}}{o}, \frac{\dot{n}}{v}\right) = .994$.

Dividing equation (4.6) by .994 gives

$$\delta_n = \frac{(2N \mp 1)\lambda}{3.853}$$
, for N = ±1, ±2, ±3 ... (4.7)

Equation (4.7) will be used below to compute the values of the plate's normal displacement.

Figures 4.10-4.13 show the plate displacement as a function of the distance from the impact point along a line from the impact point to the free edge of the plate (Section A-A in the figures) for times after impact of 4, 6, 12, and 18μ s. Also shown in these figures are the normal displacement curves based on finite element analysis which will be discussed in Section V.

Polaroid type 55 P/N film was used to photograph the double exposure holograms using a 4"x5" format view camera with a Polaroid film holder. Polaroid 55 P/N film produces both a positive and negative print. The negative print was placed in a standard photographic enlarger such that the enlarged view of the displacement fringes could be used to more accurately determine the corresponding displacement. Using the enlarger, fringes as high as N=70 could be









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Figure 4.13 - Normal Displacement, $\delta_n^{},$ Vs Distance From Point, Y, at T=18µs

observed. (Note that this technique could be conveniently expanded to include a digital X-Y plotting table as the projecting surface for the enlarger.)

In contrast to time-average holography where the white fringe denoting zero displacement is the most intense and stands out clearly. the fringe representing zero displacement in double exposure holography is of the same intensity as its neighboring higher order fringes. Hence, in order to get a quantitative plot of the displacement based on a single hologram, some a priori information on the plate's displacement response is necessary. Referring to Figures 4.1, 4.2, and 4.3, the maximum plate displacement occurs at the impact point and decreases in magnitude as one travels outward from it. Since the flexural displacement is a wave, the positive displacement at the impact point will be followed by a smaller negative one at some distance from the impact point and then, as one travels further away from the impact center, a return to the undeformed, zero displacement, portion of the plate. The peak negative displacement manifests itself by a widening of the fringes where the slope of the negative displacement goes to zero. This can be seen in Figure 4.3 in the $12\mu s$ (107) photograph. Using this type of reasoning the plate's normal displacement could be plotted. While this approach was found to be sufficient for the simple deformation pattern that the plate experienced, more complex displacements would necessitate more sophisticated approaches such as multiple double exposure holograms. As an aside, another approach that could be used to determine the zero displacement fringe would be to use an optical bench telescope

to scan across the image of the hologram. By scanning along a horizontal line passing through the impact point, the concentrically located fringes will appear to converge toward one of the circular fringes. In other words, the impact point will appear to be a fringe "source" with fringes traveling toward the one stationary circular fringe. Fringes located outside the stationary circular fringe will appear to travel in the direction of the impact point and the stationary circular fringe. The stationary fringe is a loci of zero displacement and by viewing the convergence (traveling) characteristics of the adjacent fringes, it can be located.

Figure 4.14 shows a plot of the plate's normal displacement along its free edge (Section B-B) at T=24µs after impact. The displacement curve is based on the third fringe photograph shown in Figure 4.14 and shown enlarged in Figure 4.15. The fringes are numbered in Figure 4.15. Along the free edge, the undeformed plate was used as the zero reference point. In addition, fringes that curved from one point on the free edge to another provided a convenient indicator of points of equal displacement on the opposite sides of a hill or a valley.

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Figure 4.14 - Normal Displacement Along Plate Free Edge at T=24µs



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Figure 4.15 - Enlarged View of Impacted Plate at T=24 μs Showing Numbered Fringes

SECTION V

FINITE ELEMENT ANALYSIS AND RESULTS

5.1 Finite Element Model

The numerical portion of the study was based on a finite element analysis of the cantilever plate using the general purpose finite element computer program, NASTRAN (Navy Nastran, Level 15.2.0). The model geometry and orientation for the cantilever plate is shown in Figure 5.1. The mesh consists of 304 nodes that connect the 165 quadrilateral plate elements (CQUAD2). The nodes at the base of the plate were fixed against both translation and rotation to simulate the cantilever condition. Because the impact load acts symmetrically with respect to the long axis of the plate, only half the plate was modelled with the nodes along the plate's axis of symmetry being fixed against asymmetrical motions, namely, translation in the Y direction and rotation about the X axis. These assumptions yield a finite element model having 957 degrees of freedom. Note that a refined mesh was used in the area about the impact point (shown by arrow). The plate response was essentially the same whether or not the refined mesh was used (thus demonstrating convergence) but better contour plots resulted when the finer mesh was used.

The transient analysis module of NASTRAN, Rigid Format 9, was used to carry out the analysis. When using the transient analysis module one can elect to use either a modal superposition technique or a direct integration of the nodal displacements. The latter

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Figure 5.1 - Finite Element Mesh of Cantilever Plate

technique of direct integration was adopted for this study because it would have taken a prohibitive number of normal modes and frequencies to effectively model the plate response for an impact load that had a duration of 55 μ s. A good rule of thumb when using the modal superposition method is that both the integration step size and the period of the highest normal mode should be, at most, onetenth the size of the force duration. For the present study, this would have required the highest mode of vibration to have a period of about 5 μ s, i.e., a natural frequency of 2x10⁵ Hz. This fact, coupled with the additional fact that the direct integration technique is inherently more accurate since it handles all degrees of freedom, lead to its choice as the solution technique.

The transient analysis module of NASTRAN accepts the forcing function in tabular form where the load amplitude and direction versus time are input for each node in the area of the load. For the present study, a single load in the normal (Z) direction was input as a function of time at the node designated by the arrow in Figure 5.1 (node number 171). The load profile was assumed to be the shape of a half sine wave (see Figures 4.6 and 4.7) having a duration of 55 μ s. By measuring the height of the ballistic pendulum at its release point and at its maximum rebound position from the plate, the amplitude of the half sine load can be obtained by equating the maximum kinetic energy to the maximum potential energy of the pendulum. For a pendulum of mass, m, being released at height, h₁, and rebounding to a height of h₂, equating the maximum potential and kinetic energies

for

yields a change in velocity of:

$$V_1 - V_2 = \sqrt{2g} (\sqrt{h_1} - \sqrt{h_2})$$
 (5.1)

where g is the acceleration of gravity.

The impulse of the force, F(t), acting

a time, T, is

$$I = \int_{0}^{T} F(t)dt = m (V_1 - V_2). \quad (5.2)$$

For a force having a half sine wave profile,

$$F(t) = A \sin\left(\frac{\pi t}{T}\right)$$
(5.3)

where A is the force amplitude.

Utilizing equations (5.1) and (5.3) in equation (5.2) yields

$$I = \int_{0}^{T} A \sin \frac{\pi t}{T} dt = m \sqrt{2g} (\sqrt{h_1} - \sqrt{h_2})$$
 (5.4)

Carrying out the integration and solving for

the amplitude gives:

$$A = \frac{\pi m \sqrt{2g} (\sqrt{h_1} - \sqrt{h_2})}{2T}$$
(5.5)

The mass of the steel ball was 1.335×10^{-3} slugs. From Figure 3.1, it is seen that $h_1 = 9.75$ ". The rebound height was measured by taking a photograph of the ball's trajectory while illuminating it with a high frequency strobe light. The height, h_2 , was found to be .263". Placing these values into equation (5.5)

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yields an amplitude of A = 230 lbf. Hence, the force on the plate is

$$F(t) = 230 \operatorname{Sin} \left(\frac{\pi t}{55 \mu s} \right)$$
(5.6)

Equation (5.6) was used in tabular form in NASTRAN. (This is done using the "DAREA" and "TABLED1 75" bulk data cards in NASTRAN as shown in the Appendix).

5.2 Results of the Finite Element Analysis

Using the finite element mesh, boundary conditions, and impact load profile described above, NASTRAN computed the plate displacement for specified times after impact. The output was in the form of displacements at specified nodes plus contour plots of the displacement for the entire plate. The normal plate displacement was plotted as a function of the distance (Y) from the impact point at X=3" for times after impact of 4, 6, 12, and 18µs. For purposes of comparison with the experimental results, the four plots are shown in Figures 4.10 through 4.13 of Section IV as the dashed curves. The agreement between the experimental and finite element result is quite good except for $T \approx 6 \mu s$. This is felt to be due to a stronger than average impact load for the experimental curve. This agreement is corroborated by a look at Figure 5.2 where the displacement of the plate impact point is shown plotted as a function of time. A computer generated second order least squares curve fit the finite element data exactly, demonstrating a parabolic relationship between the impact point dis-





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placement and time. The experimentally derived points closely follow this curve with the displacement at $T=6\mu s$ showing the largest deviation, as one would expect.

Figures 5.3 through 5.5 show normal displacement contours of the plate response at times after impact of 6, 8, 12, 18, 24, and $30\mu s$. The values of the contours are given in Table 5.1. The trends demonstrated by the contour plots are in good agreement with the experimental results. Note in Figure 5.5 that reflection has started to take place off the free edge for T=30µs. While some of the symbols in the contour plots may be difficult to discern, the reader can be aided by the fact that contour numbers 1 through 29 represent increasing positive displacement and numbers 30 through 50 represent increasing negative displacement. This means that a loci of zero displacement lies between contours 1 and 31, exclusive.

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TABLE 5.1

Normal Displacement Magnitude for NASTRAN Contour Plots (See Figures 5.3 - 5.5)

SYMBOL DISPLACEMENT (IN.)

SYMBOL DISPLACEMENT (IN.)

1	1.00E-05	26	9.00E-04
2	2.00E-05	27	9.50E-04
3	3.00E-05	28	1.00E-03
4	4.00E-05	29	1.05E-03
5	5.00E-05	30	-1.00E-05
6	6.00E-05	31	-2.00E-05
7	7.00E-05	32	-3.00E-05
8	8.00E-05	33	-4.00E-05
9	9.00E-05	34	-5.00E-05
10	1.00E-04	35	-6.00E-05
11	1.50E-04	36	-7.00E-05
12	2.00E-04	37	-8.00E-05
13	2.50E-04	38	-9.00E-05
14	3.00E-04	39	-1.00E-04
15	3.50E-04	40	-1.50E-04
16	4.00E-04	41	-2.00E-04
17	4.50E-04	42	-2.50E-04
18	5.00E-04	43	-3.00E-04
19	5.50E-04	44	-3.50E-04
20	6.00E-04	45	-4.00E-04
21	6.50E-04	46	-4.50E-04
22	7.00E-04	47	-5.00E-04
23	7.50E-04	48	-5.50E-04
24	8.00F-04	49	-6.00E-04
25	8.50E-04	50	-6.50E-04



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Figure 5.5 - NASTRAN Contour Plot of Normal Displacement at T=24 μs and T=30 μs

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SECTION VI

DISCUSSION AND CONCLUSION

The work described in the preceding sections has demonstrated that double pulsed holographic interferometry can be effectively used to study the dynamic structural response of an elastic body subjected to impact loading. Within the limits of the displacement range covered by pulsed laser interferometry using a ruby laser (5-1000 μ in), quantitative displacement information describing a plate's initial response to an impact load was obtained. There was good agreement between the experimental tests and analytical results obtained using the NASTRAN finite element computer program (Rigid Format 9). Some scatter between individual tests did occur and was felt to be due to failure to accurately reproduce the impact load on the plate. Future work in this area should strive for a more repeatable impact load. In addition, experimental timing measurements should be increased to a sensitivity of \pm 0.1 μ s instead of the \pm 0.5 μ s used in the present experimental tests.

The good experimental/analytical agreement provides increased confidence in NASTRAN's transient analysis module. The good agreement does not come free, however. For a typical computer run (see Appendix), central processor (CP) time was 923 seconds and input/output (IO) time was 1360 seconds on the Wright-Patterson AFB CDC 6600 Computer.

Future work in the vein of the current research will use

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the existing system to study turbine fan blade response to impact load. Some thought is also being given to utilizing the measurement of the plate flexural wave speed to determine elastic material properties of composites (say) and, also, to study material damping characteristics. Finally, plate displacements, at times greater than those dealt with in this report (2-30µs), could be studied using the double-pulse capability of AFAPL's ruby laser.

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APPENDIX

NASTRAN Program Listing

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12-	COUADS	227	-	5+2	260	261	250					
	COMAD2	228		256	261	262	25:					
	COUAD?	229		251	262	263	252					
	COMANS	236		262	263	264	263					
16-	COULDO	236		259	570	112	266					
- 2 -		110			140	010	+ 90					
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- 2	COURDS	240		263	574	512	264					
-:-	COUAC2	546	-	274	281	-282	211-			-		
-22-	COUAD2	247	1	271	282	283	272					
-5-2-	000005	248		212	283	284	273					
-+2	COUAD2	543		273	284	285	274					
25-	SOUA S	25.	+	-274-	285	286	275			1		
-92.	COUAD2	5.0	1	201	292	293	282					
-+2	204000	152	-	292	£63	+63	283					
23-	COUAD2	259	1	263	294	285	284					
-62	COUD12	- 556		284	265	902	245			-	-	
	200000	26.		205	596	262	286					
	CUBINO.	966		999	100		100					
-25-	COULD	267		293	304	305	294					
	CC01100	26.8		994	385	305	200					
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- 95	201000	212		20.0	+ 1 10	610	1 1					
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- 951	CHUACS		-	5.5	210	317	315					
39-	COUAD2-	979	-	3.6	317	318	361					
- 41	COUADZ	280	+	347	318	319	30.8					
-101	204000	286		314	325-	326	315					
-241	204000	282	1	315	326	327	316					
	204000	200	-	316	327	320	317			1		
- + + 1	COUA 22	259	1	317	328	329	318					
46	500402	562		31.6	429	330	319					
46	204000	296		5042	336	122	325					
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GRID 1		3.3000 .9000	
	26	3.3300 1.20rG .	.0000
I 0145		3.3196 1.5000	
GRID 20	14	3.4500 .0000	0000.
GRID 21		3.45:0 .3000	
GRID 2	9	3.450 .6000	.6600
2 01 35			
GRID 21	E.	3.4500 1.2000 .	0000.
GR10 21	60	3.4500 1.5000	.000
GRID 21	2	3.6400 .0000	.0000
GRID Z	91	3.61.00 .3000	
CI49	21	3.6:00 .6000	
0410 21	0		
2410	0	3.6455 1.2004	
OF NO		3.0001 1.000	0.0.0.1
GRID 23	56	. 7500 . 0000	.0000
50105		3.7596 .3666 .	.6000
GRID 2	2.4	3.7500 .6003 .	.000
66.10 2i	6		.2000
SRID 2	31	3.7506 1.2006	
6610 2	31	3.7500 1.5000	.0606
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342- 346- 346- 346- 346- 346- 346- 346- 346	GRID	21.2	3 4	5	9	 8	6	. 10
28 28 28 28 28 28 28 28 28 28 28 28 28 2	6610	248	4.0530	. 00 00	.0000			
384- 3855 3855 3859 3110- 3110- 3110- 3110- 314- 314-		549		- 36.6E	-0000			
365- 306- 319- 310- 310- 311- 314- 314-	GRID	250	4.0520	.6100	- 2000			
346- 346- 346- 346- 346- 346- 346- 346-	0110	142		03964	0100			
309- 310- 311- 312- 312- 314-	CBID	25.5	4. CEAC	. 5000				
316	CETO	254	4.211	1111	.0000			
316- 312- 314- 314-	0100	266	4.2006	3010	0000			
312- 312- 314-	GRID	261	4.21.0	.65 05	.000			
314-	6810	262	4.2040					
-1 12	GRID	263	4.2000	1.2000	.0000			
31 4-	CEID	261	4.200	1.500	0000			
	GRID	270	4.3500	.66600	0000.			
315-	6140	271	4.3550	-3543				
316-	GRID	272	4.3500	.60.39.	.0000			
31.7-	Clas	273	4.3540	.900	.0000			
31.8-	GFID	274	4.3500	1.20(0	.0000			
319-	CRID	275	1.1564		0000			
32f -	GRID	241	4.51.20	5070.	.3630			
321-	GEID	-282	4.5100	-3360	0090.			
322-	GEID	283	4.5000	. 60 00	.0000			
323-	6810	-284	4.56.0	9696.	-0000			
324-	GRID	285	4.5026	1.2020				
				9996				
-026	0115	963			0000.			
10 8-	CPID	204	4. 4125	. 66.00	1010-			
	Celo	500	4.4125					
330-	01 45	296	4. 9125	1.2000	.0000			
-131-	01-10	103	521010	1.5960	0000			
132-	GP 10	30.3	5.1256	.0030	.00.00			
333-	0145	304	5.1256	-3006.	0000.			
334-	GRID	305	5.1250	.60.00	.0000			
	0149	905	N621.6	.90.90	0000.			
530-	GKID	307	1421.4	1.02.1				
- 118-	0100	216	5.4775		10000			
	0100	316	5113	2002	0000			
346-	GRID	316	5.4375	.6030	0000			
341-	61.99		526495	3006.	.0060		-	
342-	GRID	31.4	5.4375	1.2000	• 25,50			
	01-5		526435	1.5666	•6680			
344-	GRID	325	5.7596	.0000	.00.00			
345	0105			30.96				
346-	GFID	327	5.7503	. COC				
-242	6F10	326	9432.6	.946.	0339.	-		
345-	CIJ	329	5.7530	1.2006	.0000			
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COPY AVAILABLE TO DDC DOES NOT PERMIT FULLY LEGIBLE PRODUCTION
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5			1.2006	1.5600	.0006	-36.66	.65 60	0006.	1.2030			1001	.6005		1.2000	1.5000	0000.		- 6000	1.2015	1.5000				116	204	292	THRU	1976	C1/1-1	9666 . 1	6166	1164.1				
	6 1625	6.6625	6.0625	6.6625	6.375C	6-3756-	6.3750	0.3756 -	6.3750	04/200	6.6475	6-6875	6.6475	6149 · 9	6.6975	6.6875	1.00.0		1.11.1	7.0135	7.6305			6191.	165	£61	261	909 6	7 0.6	0-0-0	276		46.0-6	CINUT	1.6-6		
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