DPEARTMENT OF MECHANICAL ENGINEERING & MECHANICS
COLLEGE OF ENGINEERING & TECHNOLOGY
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23529

NONLINEAR ANALYSES OF COMPOSITE AEROSPACE STRUCTURES IN SONIC FATIGUE

LANGLEY GRANT
IN-05-CR
109250
P.13

By

Chuh Mei, Principal Investigator

Progress Report
For the period December 16, 1991 to June 15, 1992

Prepared for
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23665

Under
Research Grant NAG-1-1358
Dr. Stephen A. Rizzi, Technical Monitor
ACOD-Structural Acoustics Branch

Submitted by the
Old Dominion University Research Foundation
P.O. Box 6369
Norfolk, Virginia 23508-0369

June 1992

(NASA-CR-190565) NONLINEAR ANALYSES OF COMPOSITE AEROSPACE STRUCTURES IN SONIC FATIGUE Progress Report, 16 Dec. 1991 - 15 Jun. 1992 (Old Dominion Univ.) 13 p

N92-30209

Unclas
G3/05 0109250

NONLINEAR ANALYSIS OF COMPOSITE AEROSPACE STRUCTURES IN SONIC FATIGUE

by
Chuh Mei*

This report summarizes the semiannual research progress, accomplishments and future plans performed under the NASA Langley Research Center Grant No. NAG-1-1358, entitled, "Non-linear Analysis of Composite Aerospace Structures in Sonic Fatigue," for the period December 16, 1991 to June 15, 1992. The primary research effort of this project is the development of analytical methods for the prediction of nonlinear random response of composite aerospace structures subjected to combined acoustic and thermal loads. The progress, accomplishments and future plans on three random response research topics are discussed, followed by presentations and degrees earned.

1. ACOUSTICS-STRUCTURE INTERACTIONS USING BOUNDARY/FINITE ELEMENT METHODS

The Boundary Element Method (BEM) is a good approximating technique that is widely used in the solution of acoustic field problems. BEM needs less grid generation and computational time, and is perfectly suited to study far-field acoustics. Over the past ten years, interest in boundary element techniques has been very popular.

In the development of the newer supersonic and hypersonic flight vehicles, an increased need for the analysis of acoustic fields and the response of structures to acoustic loads has become necessary [1,2]. Research in the analysis of these acoustic fields in ducts has dominated much of the boundary element research. The first objective is to study the boundary element method for acoustic problems in a two-dimensional field. Many types of problems with complicated boundary conditions were investigated. All of the selected problems had exact solutions. These exact solutions were used to validate the boundary element method as an accurate approximating method. Two types of elements were used: constant elements and linear elements. Both types of elements gave very good approximations for all selected problems. As expected, the linear

* Director of Center for Structural Acoustics and Fatigue research, and Professor of Department of Mechanical Engineering and Mechanics.

elements produced less error than the constant elements for all of the problems. For one problem, a frequency graph was plotted for linear elements and compared with the exact solution shown in Figure 1. The linear elements exactly predicted the pressure for wavenumbers less than 2. For higher wavenumbers, the pressure values begin to deviate from the exact solution slightly. From running different cases of varying wavenumbers, an important thing was learned about element discretization. There must be at least four elements per wavelength to give accurate solutions.

The next stage in research was to expand the domain problem to ducts with sudden area changes. Two basic muffler type problems were selected for comparison with the boundary element method. In each case, constant and linear element results were compared with the exact solutions. For both problems, the constant and linear results gave very good approximations for low wavenumbers. Since the number of elements did not change, it was expected that the results would deviate from the exact solution as the wavenumber increased. This was evident in the frequency plots as the wavenumber increased. After validating the boundary element method for sudden area changes in ducts, a three-section duct problem was selected where no exact solutions exist, Figure 2. The transmitted pressure was studied as the angle of the mid-section was rotated. As the angle increased from 0 to 45 degrees, it was expected that the transmitted pressure would decrease exponentially. As seen in Figure 2, the pressure did decrease very rapidly as the angle increased. This type of duct problem was selected to show that the boundary element method can handle a wide range of very complicated problems.

The next research phase is to study three-dimensional duct problems with exact solutions. This has been done for very simple problems. The computer code is now being updated to handle more complicated three-dimensional problems. Research is also being done in the area of combining finite and boundary element methods, finite element for modeling structures and boundary element for modeling acoustics. Interactions between acoustics and structures thus become at ease. This seems to be a very fast growing concept because boundary elements and finite elements both offer special features that compliment each other. By combining the two methods, more realistic and complicated problems can be handled. The boundary element technique has been shown to be a very powerful numerical technique, mainly because dimensionality is reduced by one.

Some future plans include the modeling of the TAFA facility at NASA Langley, which will include the application of a thermal load. The structural acoustic coupling will be extended to include composite panels.

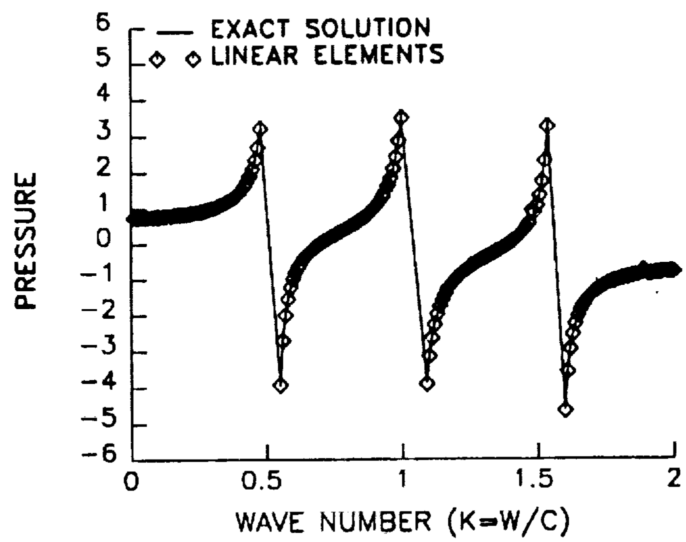

Fig. 1 Frequency Response of an Open Outlet Duct

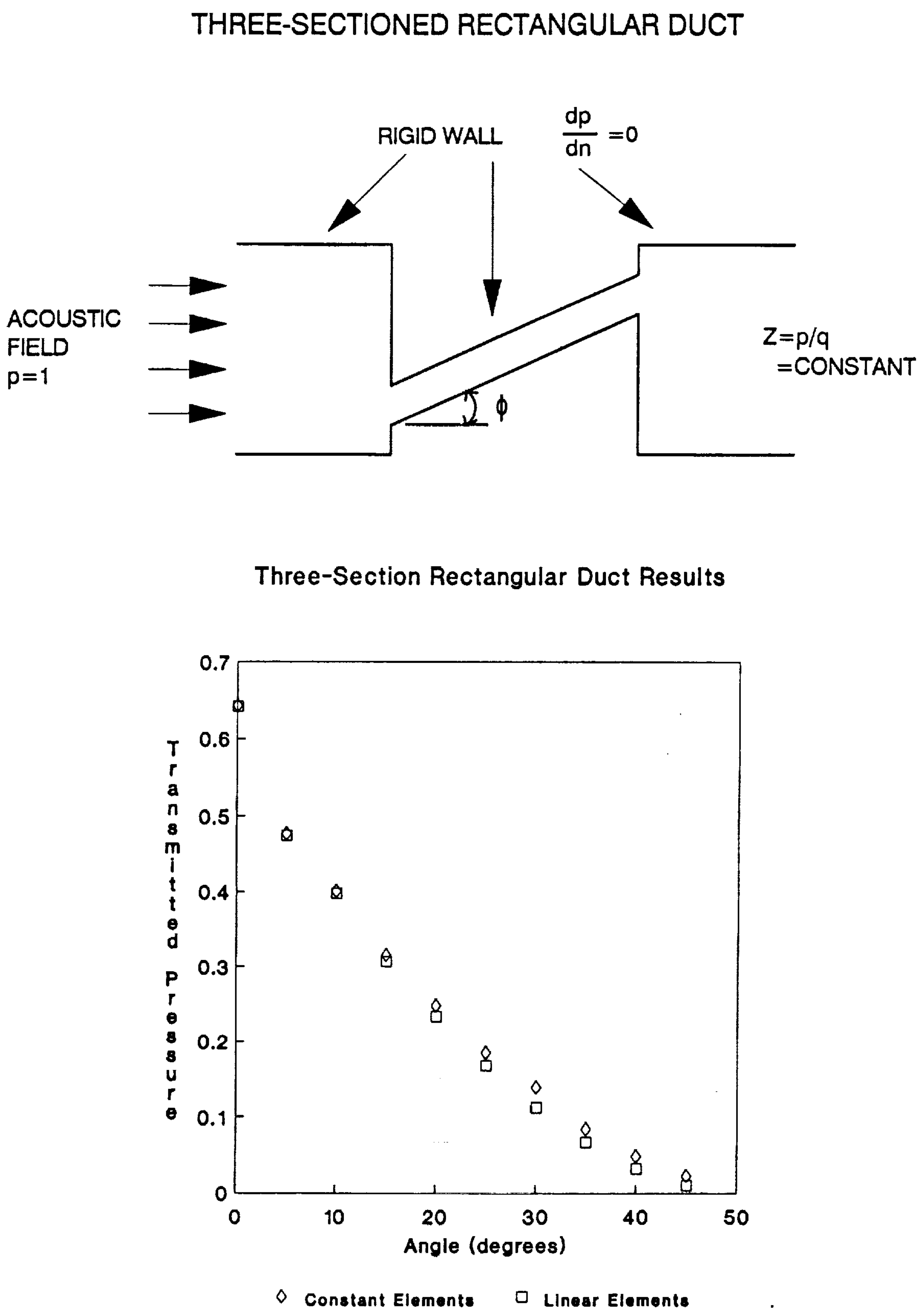

Fig. 2 A Three-Section Duct Problem

2. NONLINEAR VIBRATIONS OF BEAMS AND COMPOSITE PLATES UNDER HARMONIC AND RANDOM EXCITATIONS

Beams and plates begin to show nonlinear effects when the maximum displacement reaches approximately the thickness of the specimen. When larger displacements are observed the effects of the non-linearities become more pronounced and must be considered in any type of analysis. These considerations become even more challenging when the beam or plate is compressed in the inplane direction and the specimen is observed to buckle. Buckling can occur as a result of a mechanical or a thermal load, and when coupled with large amplitude vibrations produces a highly nonlinear system. This type of system is characterized by various nonlinear responses, such as internal resonance, combination resonance and dynamic snap through phenomena.

This type of problem has recently attracted increased attention with the development of hypersonic and high supersonic flight vehicles. The problem is also complicated by the fact that the loads that these aircraft encounter are random loads and can not be treated as sinusoidal or periodic in nature. In order to begin the study problems of this nature, a basic research has begun with the nonlinear vibrations of a buckled beam. First, the static case of the buckled beam had to be analyzed to determine the relationships between the axial and lateral deflection of the beam. This was accomplished by applying the Galerkin's method to solve the equilibrium equations. Results of this analysis were compared to those obtained experimentally and by Yamaki et al. [3] for the case of a clamped Aluminum beam shown in Figure 3.

The next stage of the research which is presently being conducted is to solve the problem of the vibrating buckled beam under a harmonic excitation. This is being done using either a two- or three-mode solution employing the harmonic balance method. Work is also being conducted to verify this investigation with experimental results that will be obtained in the vibrations lab at ODU. This work will also be compared with results obtained by Yamaki et al. [4] since their experimental work appears to be the most complete and though. Additional work in this area will also be conducted by exposing the beam to random base excitation and a similar comparison to analytical results will be made. It is the goal to have this work completed by the end of September, 1992.

The next research phase to be accomplished will be to expand both the analytical and experimental already under progress to the buckled plate. Work with the plate will begin with the analysis of a composite plate excited by harmonic and then a random load. The experimental work for this portion of the research will take place next summer at Wright Labs in Dayton, Ohio. This will occur since the shakers available in the vibrations lab at ODU will not have enough power to vibrate a buckled composite plate to the necessary amplitude.

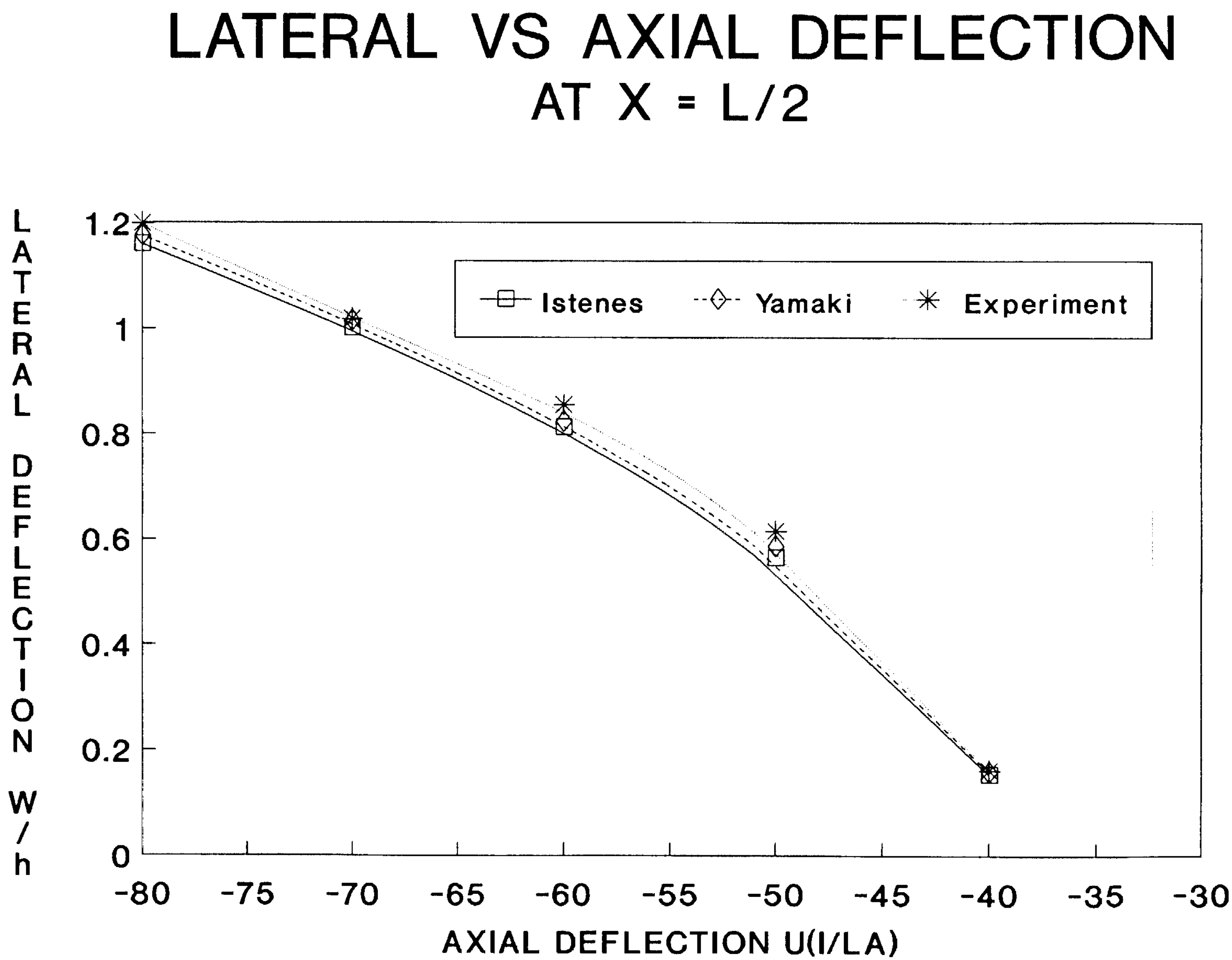

Fig. 3 Comparison of Maximum Deflection and Axial End Displacement of a Clamped Beam

3. NUMERICAL SIMULATION OF THE NONLINEAR RESPONSE OF COMPOSITE PLATES UNDER COMBINED THERMAL AND ACOUSTIC LOADING

The proposed future generation of aerospace vehicles will subject their structural components to extreme operating conditions [2]. These conditions, typically, imply high thermal loads and dynamic loads occurring simultaneously, with the dynamic loads usually being random in nature. The extreme nature of these loads drive the structural response into nonlinear regions. There is, hence, a need for nonlinear analysis to be used since linear theories significantly over estimate responses and therefore underestimate fatigue life characteristics. Furthermore, high order statistics, beyond means and mean squares, are required in order to predict fatigue life of structures exhibiting nonlinear behavior. Towards this objective, one of the tools we have is the numerical integration of the nonlinear governing equations that describe the system. The purpose of this study, therefore, is to give a complete characterization of the nonlinear response of a composite laminated panel exposed to high thermal and acoustic loads by numerical simulation techniques.

Recent work done in this area using numerical simulation has been reported by Jay Robinson [5]. He presented solutions for the nonlinear response of a laminated plate subject to random loading using the finite element method. The present study aims to improve on this considerably by broadening the scope of the problem. Thermal loading is accounted for, along with an initial stress distribution in the panel. The possibility of the panel not being perfectly flat is accommodated for by assuming an initial lateral imperfection. Variation of material properties of the lamina with temperature are modelled in discrete steps — with the values corrected for fixed increments in temperature. Whereas previous work done has simulated a uniform, Gaussian white noise random loading, normally incident on the panel, the load distribution will be improved here to have an angle of incidence. Additionally, in place of a uniform spatial distribution, the pressure will be varied along the length of the panel to portray a decay in the excitation level from the leading edge (near the source) to the trailing edge. Tests at TAFA seem to indicate no significant variation in pressure levels along the width of the panel. Hence, we will hold the pressure distribution uniform along the width of the plate. Apart from these the pressure will be modelled as a stationary Gaussian white noise loading.

As far as the panel itself is concerned, all the assumptions of plane stress conditions are valid. The theory is restricted to small strains and rotations. von Karman's large deflection strain-displacement relationships have been applied, with transverse shear and rotatory inertia assumed negligible. Thus, the displacement field is as follows:

$$u(x,y,z,t) = u_o(x,y,t) - zw_{,x}$$

$$v(x,y,z,t) = v_o(x,y,t) - zw_{,y}$$

$$w(x,y,z,t) = w(x,y,t) + w_o(x,y)$$

where u_o and v_o are midplane longitudinal displacements and w is the lateral deflection, w_o is the prescribed initial imperfection. The displacement functions are expressed in terms of nodal coordinates, a_i, with appropriate interpolation polynomials (bilinear, bicubic, etc.) with this displacement-field and a linear stres-strain relationship, the force and moment resultants are given by

$$N_i = N_i^m - N_i^t + N_i^o$$

$$M_i = M_i^m - M_i^t + M_i^o$$

where the superscripts m, t and o stand for stresses developed due to mechanical strain; due to thermal loading and the prescribed initial stress distribution, respectively.

The equations of motion are derived using a modified Hamilton's principle expression with a weighted integration from initial time to final time, ie:

$$\delta \int_{t1}^{t2} W(t)(T - U - V + D)dt = 0$$

where W(t) is the weighting function and T, U, V and D are the kinetic energy, strain energy, potential of the external load and the dissipative energy (due to damping), respectively.

The numerical integration uses a single-step algorithm where at time-step n+1,

$$a_{n+1} = \sum_{q=0}^{p-1} \frac{d^q a_n}{dt^q} \frac{\Delta t^q}{q!} + \alpha_n^p \frac{\Delta t^p}{p!}$$

where a_n is the solution from the previous time step, and

$$\frac{\int_{t_1}^{t2} w(t)\Delta t^q dt}{\int_{t_1}^{t2} w(t)dt} = \theta_q \Delta t^q$$

where θ_q being free integration parameters. Using the above expression in Hamilton's principle results in a set of nonlinear algebraic equations in α_j as follows:

$$A_{ijkl}\,\alpha_j\alpha_k\alpha_l + B_{ijk}\alpha_j\alpha_k + C_{ij}\alpha_j + D_i + P_i = 0$$

where P_i is the load vector. Within each time-step this set of coupled nonlinear equations is solved using the Newton-Raphson iterative technique, and a_i is updated accordingly.

This is as far as work has been done in the study presently. For the immediate future, this formulation will be modified to include effects of transverse shear strains retaining the von Karman large displacement theory. As a next step the plans to improve load simulation will be concretized and the variation in pressure distribution will be clearly defined. Further, we hope to extend the application of the finite element model to panels of irregular shapes by using Discrete Kirchoff Triangular elements [6,7]. Towards that, its capabilities as a shear element need to be well understood. With these decided the system response will be characterized by the mean, rms, skewness, kurtosis, probability density function, peak probability distributions, spectral deanities, crossing rates and correlations for the maximum deflection and maximum strain.

4. PRESENTATION AND DEGREES

Mr. Carl S. Pates, III and Mr. Raymond R. Istenes received their Master of Engineering degrees in Engineering Mechanics in December 1991 and May 1992, respectively. Carl Pates also received the Jefferson Goblet Student Paper Award and presented a paper at the 33rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Dallas, TX April 13-15, 1992. Title of the paper is "Acoustic Analysis of Two-Dimensional Ducts with Sudden Area Changes using the Boundary Element Method," Proceedings of the 33rd Structures, Structural Dynamics and Materials Conference, Dallas, TX, April 1992, pp. 360-368.

REFERENCES

1. Clarkson, B.L., "Review of Sonic Fatigue Technology," NASA Langley Research Center, March 1990.

2. Mixson, J.S. and Roussos, L.A., "Acoustic Fatigue: Overview of Activities at NASA Langley," NASA TM 89143, April 1987.

3. Yamaki, N. and Mori, A., "Nonlinear Vibrations of a Clamped Beam with Initial Deflection and Initial Axial Displacement, Part I: Theory," Journal Sound and Vibration, Vol. 71, 1980, pp. 333-346.

4. Yamaki, N., Otomo, K. and Mori, A., "Nonlinear Vibrations of a Clamped Beam with Initial Deflection and Initial Axial Displacement, Part II: Experiment," Journal Sound and Vibration, Vol. 71, 1980, pp. 347-360.

5. Robinson, J.H., "Finite Element Formulation and Numerical Simulation of the Large Deflection Random Vibration of Laminated Composite Plates," Master's Thesis, Old Dominion University, 1990.

6. Jeyachadrabose, C. and Kirkhope, J., "An Alternative Explicit Formulation for the DKT Plate-Bending Element," International Journal for Numerical Methods in Engineering, Vol. 21, 1985, pp. 1289-1293.

7. Batoz, J.L., Bathe, K.J. and Ho, L.W., "A Study of Three-Node Triangular Plate Bending Elements," International Journal for Numerical Methods in Engineering, Vol. 15, 1980, pp. 1771–1812.