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Final Report
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Nonlinear Aeroelasticity of Composite Wings

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June 10, 1993 - December 9, 1996

1 Background

The general problem of modeling the steady and unsteady behavior of advanced composite wings poses a considerable challenge to the analyst, both in developing an analytical/numerical model of the system and in understanding the complicated physical behavior. The large deflections of flexible wings complicate the analyses of both the structure and the flowfield. The conventional small-disturbance analyses are no longer valid, and neither is the approach of assuming that the problem can be solved by two independent groups, one modeling the structure and the other modeling the flowfield.

Accurate evaluations of modern concepts for aircraft require the use of nonlinear structural models that account for large deflections and rotations, anisotropic and nonhomogeneous materials, and the complicated coupling that typically occurs among the various modes associated with bending, twisting, and extension. Accurate evaluations of modern concepts also require the use of nonlinear models that provide time-accurate simulations of the flowfield which are not restricted to small (sometimes harmonic) disturbances and which accurately imitate the highly three-dimensional, vorticity-dominated flows. And most importantly, the master model of the aircraft system must treat the flowing air; the structure; and the control surfaces, their driving motors, and their control laws as elements of a single dynamic system. All of the governing equations must be solved simultaneously and interactively in the time domain.

We have developed a scheme that couples the codes for aerodynamic and aeroelastic analyses so that the flowfield and the positions and velocities of points on the lifting surface are predicted simultaneously and interactively. The actual structural-dynamic/aerodynamic coupling is carried out by representing the deflection of the wing as an expansion in terms of a few low-frequency free-vibration modes, especially the ones involved in internal resonances. The time-dependent coefficients in this expansion are then regarded as the generalized coordinates. The aerodynamic loads are also expanded in terms of the linear modes. Integration over the spatial domain reduces the problem to one of several degrees of freedom governed by ordinary-differential equations with generalized forces. An integration scheme is developed and applied to this set of equations.

In nonlinear, multi-degree-of-freedom systems, very unusual behavior can occur when the natural frequencies, ω_i, are related by expressions of the following form: $\omega_i \pm \omega_j = \omega_k$ for quadratic nonlinearities and $\omega_i \pm \omega_j \pm \omega_k = \omega_l$ for cubic nonlinearities. Both Minguet and Dugundji[1] and Cole[2] observed strange behavior in aeroelastic systems when these frequency relations were satisfied.

Working in a wind tunnel at NASA Langley, Cole[2] investigated the effectiveness of spoiler surfaces in suppressing the onset of flutter for a low-aspect-ratio, rectangular wing in a wind-tunnel test. Instead of preventing flutter as he desired, the spoiler drastically lowered the flutter boundary and produced a torsional instability. Inspecting the natural frequencies of the wing reveals that the frequency of the second bending mode is approximately twice the frequency of the first torsional mode, suggesting that a two-to-one internal resonance is responsible for the instability.

To verify this, we have investigated the nonlinear response of a cantilever metallic plate to a base excitation. As a first step, we found experimentally and theoretically the linear natural frequencies and mode shapes of the plate. The frequencies and mode shapes obtained experimentally match those obtained theoretically; the differences in the corresponding frequencies are less than 3%. The frequency of the second bending mode is 59.70 Hz, and the frequency of the first torsional mode is 31.75 Hz. These natural frequencies are nearly in the ratio of two to one, suggesting the possibility of activating the two-to-one internal resonance, and hence, producing a torsional instability, as in Cole's study.

The plate was excited using a 2000-lb table shaker, and the input force was monitored using an accelerometer. The response of the plate was measured using a laser vibrometer. We observed that by sweeping the excitation frequency or amplitude upward near the resonance of the second bending mode, we were able to excite the torsional mode of the plate. This phenomenon was identified by time histories, power spectra, autocorrelograms, and state-control plots and was further characterized by force-response plots. The indirect excitation of the torsional mode is similar to that observed by Cole. Therefore, we have shown experimentally that an antisymmetric vibration mode of a cantilever metallic plate can be indirectly excited by a two-to-one internal-resonance mechanism.

References

1. Minguet, P. and Dugundji, J., 'Experiments and analysis for composite blades under large deflections, part 1— static behavior,' *AIAA Journal* 28, 1990, 1573-1579.

2. Cole, S. "Effects of Spoiler Surfaces on the Aeroelastic Behavior of a

Low-Aspect-Ratio Rectangular Wing," AIAA Paper No. 90-0981-CP, 1990.

2 Other Developments Resulting from the AFOSR Sponsored Research

We have secured a Contract with Cessna to develop numerical, time-domain simulations that capture the interactions among aerodynamics, rigid-body dynamics, structural dynamics, and control systems. In these simulations all of the elements mentioned above are viewed simply as the components of a single dynamic system. All the governing equations can be nonlinear, motions are not restricted to be small nor harmonic, post-flutter behavior can be simulated, and flutter suppression can be simulated. All work leads to the distant goal in which a maneuvering aircraft can be simulated without resorting to wind-tunnel and flight tests.

3 Students Receiving Full or Partial Support

The following students received full or partial support from the AFOSR Grant. The support took the form of stipends paid directly to them.

Senior Projects

Popovic, P., 1994 "An Experimental Investigation of Energy Transfer from a High-Frequency Mode to a Low-Frequency Mode in a Flexible Structure"

Masters Students

1. Nayfeh, S., 1993, "Nonlinear Dynamics of Systems Involving Widely Spaced Frequencies"
2. Kreider, W., 1995, "Linear and Nonlinear Vibrations of Buckled Beams"

Doctoral Students

1. Anderson, T. J., 1993, "Nonlinear Vibrations of Metallic and Composite Structures"
2. Oh, K., 1994, "A Theoretical and Experimental Study of Modal Interactions in Metallic and Laminated Composite Plates"

3. Tabaddor, M., 1996, "Nonlinear Vibration of Beam and Multibeam Systems"

4. Pratt, J., expected 1997.

4 Publications

The following articles were made possible by full or partial support from the AFOSR Grant.

Refereed Articles in Technical Journals and Proceedings for Which the Entire Manuscript is Reviewed

1. C. Chin, A. H. Nayfeh, and D. T. Mook, "The Response of a Nonlinear System with a Nonsemisimple One-to-One Resonance to a Combination Parametric Resonance," International Journal of Bifurcation and Chaos, Vol. 5, No. 4, 1995, pp. 971-982.

2. A. H. Nayfeh, C. Chin, and D. T. Mook, "Parametrically Excited Nonlinear Two-Degree-of-Freedom Systems with Repeated Natural Frequencies," Shock and Vibration, Vol. 2, No. 1, 1995, pp. 43-57.

3. P. F. Pai and A. H. Nayfeh, "A New Method for the Modeling of Geometric Nonlinearities in Structures," Computers & Structures, Vol. 53, No. 4, 1994, pp. 877-895.

4. A. H. Nayfeh and C. Chin, "Nonlinear Interactions in a Parametrically Excited System with Widely Spaced Frequencies," Nonlinear Dynamics, Vol. 7, No. 2, 1995, pp. 195-216.

5. C. Chin and A. H. Nayfeh, "Parametrically Excited Nonlinear Two-Degree-of-Freedom Systems with Nonsemisimple One-to-One Resonance," International Journal of Bifurcation and Chaos, Vol. 5, No. 3, 1995, pp. 725-740.

6. K. Oh and A. H. Nayfeh, "Nonlinear Combination Resonances in Cantilever Composite Plates," Nonlinear Dynamics, Vol. 11, No. 2, 1996, pp. 143-169.

7. T. J. Anderson and A. H. Nayfeh, "Natural Frequencies and Mode Shapes of Laminated Composite Plates: Experiments and FEM," Journal of Vibration and Control, Vol. 2, No. 4, 1996, pp. 381-414.

8. K. Oh, A. H. Nayfeh, and D. T. Mook, "Modal Interactions in the Forced Vibration of a Cantilever Metallic Plate," submitted for publication, Journal of Vibration and Acoustics.

Conference Papers and Presentations

1. N. E. Sanchez and A. H. Nayfeh, "Global Behavior of a Biased Nonlinear Oscillator Under External and Parametric Excitations," Society of Engineering Science 31st Annual Technical Meeting, College Station, TX, October 10-12, 1994.

2. A. H. Nayfeh and C. Chin, "Nonlinear Interactions in a Parametrically Excited System with Widely Spaced Frequencies," Society of Engineering Science 31st Annual Technical Meeting, College Station, TX, October 10-12, 1994.

3. K. Oh, A. H. Nayfeh, and D. T. Mook, "Modal Interactions in the Forced Vibration of a Cantilever Metallic Plate," ASME Winter Annual Meeting, Chicago, IL, November 6-11, 1994.

4. K. Oh, A. H. Nayfeh, and D. T. Mook, "Modal Interactions in the Forced Vibration of a Cantilever Metallic Plate," in *Nonlinear and Stochastic Dynamics*, AMD-Vol. 192/DE-Vol. 78, 1994, 237-247.

5. P. Popovic, A. H. Nayfeh, K. Oh, and S. A. Nayfeh, "An Experimental Investigation of Energy Transfer from a High-Frequency Mode to a Low-Frequency Mode in a Flexible Structure," Fifth Conference on Nonlinear Vibrations, Stability, and Dynamics of Structures, VPI&SU, Blacksburg, VA, June 12-16, 1994.

6. A. H. Nayfeh, "Can the Design Engineer Ignore Nonlinear Phenomena," Second Biennial European Joint Conference on Engineering Systems Design and Analysis, London, England, July 4-7, 1994.

7. A. H. Nayfeh, "Can the Practicing Engineer Ignore Nonlinear Phenomena," First Industry/University Symposium on High Speed Civil Transport Vehicle, Greensboro, NC, December 4-6, 1994.