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SUMMARY OF ACCOMPLISHMENTS - FINAL REPORT

1978-1982

NASA Research Grant NSG-1578

Response Studies of Rotors and Rotor Blades With Application to Aeroelastic Tailoring

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Summary of Accomplishments for the Period 1978-1982
Under NASA Research Grant NSG-1578, Title:
"Response Studies of Rotors and Rotor Blades with Application to Aeroelastic Tailoring"

1. Introduction and Overview

Under NASA Research Grant NSG-1578, which was initially funded on Dec. 1, 1978 and expired on November 30, 1982 various tools for the aeroelastic stability and response analysis of rotor blades in hover and forward flight were developed. These tools were finally incorporated in a comprehensive package capable of performing aeroelastic tailoring of rotor blades in forward flight. The results indicated that substantial vibration reductions, of order 15-40%, in the vibratory hub shears can be achieved by relatively small modifications of the initial design. Furthermore the optimized blade can be up to 20% lighter than the original design.

The various aspects of this research effort have been reported in a series of publications, Refs. 1 through 11. The major thrust of this research was concentrated on four topics which are listed below:

1. Finite element modeling of rotary-wing aeroelastic problems in hover and forward flight (Refs. 1-3).

2. Development of numerical methods for calculating the aeroelastic response and stability of rotor blades in forward flight (Refs. 4-6 and 9).

3. Formulation of the helicopter air resonance problem in hover with active

controls (Ref. 7).

4. Optimum design of rotor blades for vibration reduction in forward flight. (Refs. 8, 10 and 11).

The major accomplishments in these four subject areas are briefly summarized in the following sections. Finally additional accomplishments are summarized in the concluding section.

2. Finite Element Modeling of Rotary-Wing Aeroelastic Problems in Hover and Forward Flight

A detailed description of this research can be found in Refs. 1-3. In the course of this research a finite element method for the spatial discretization of the dynamic equations of equilibrium governing rotary-wing aeroelastic problems was developed. The equations of motion are nonself-adjoint, nonlinear, and in partial differential form. For this class of problems, variational principles are not available. Thus, formulation of the finite element equations is based on weighted Galerkin residuals. This Galerkin finite element method reduces algebraic manipulative labor significantly, when compared to the application of the global Galerkin method to similar problems. However, more computer time is spent on the numerical calculations.

To illustrate the application of the Galerkin finite element method, the coupled flap-lag aeroelastic stability boundaries of hingeless helicopter rotor blades in hover was calculated. The finite element method was used to remove the spatial dependence from the equations. The ensuing set of nonlinear, ordinary differential equations was linearized about an appropriate nonlinear static equilibrium position. The number of nodal degrees of freedom in the discretized system was reduced significantly through a normal mode transformation. The nonlinear static equations, determining the equilibrium position, were solved iteratively using the Newton-Raphson method. The linearized dynamic equations were reduced to the standard eigenvalue problem from which the aeroelastic stability boundaries are obtained.

The convergence properties of the Galerkin finite element method was studied numerically by refining the discretization process. The results indicated that four or five elements suffice to capture the dynamics of the blade with the same accuracy as the global Galerkin method. However, for a reliable analysis, two modes for each elastic degree of freedom are required, since the second lag mode determines system stability for certain values of elastic coupling.

Next, the method was applied to the more practical coupled flap-lag-torsion aeroelastic stability and response problem of hingeless helicopter rotor blades in trimmed forward flight. Emphasis was placed on consistent discretization of the torsional degree of freedom.

When this study was performed, no previous finite element solutions for the stability and response of nonlinear, nonconservative systems with periodic coefficients were available. Therefore, the general formulation was specialized to the coupled flap-lag problem in forward flight which was used to establish the computational feasibility of the Galerkin finite element method in the forward flight regime.

The nonlinear, periodic coefficient, finite element equations were linearized about a nonlinear time dependent equilibrium position, namely, the steady-state response of the system. This response is obtained iteratively using quasilinearization. Aeroelastic stability was determined from the linearized perturbation equations using Floquet theory.

The most important conclusions obtained in this study were:

- The Galerkin finite element method is a practical and powerful tool for formulating and solving rotary-wing aeroelastic problems. Since spatial discretization is applied directly to the partial differential equations, algebraic manipulative labor is reduced significantly when compared to the application of the global (or conventional) Galerkin method to similar problems. However, more computer time is spent in calculations, in particular, when dealing with forward flight. The increase of computer time is roughly 30% and therefore it is not considered significant in view of the ever increasing capabilities of modern computers.

- Four or five elements are sufficient to capture the bending dynamics of the blade, when torsion is included six elements are needed to yield an accuracy similar to the global Galerkin method.

- Normal mode transformation, combined with the Galerkin finite element formulation, reduces the number of nodal degrees of freedom significantly and enables one to deal efficiently with complex problems. Complete freedom regarding the number of modes to be used is retained. Thus the method is particularly suitable for modeling bearingless flexbeam-type rotors.

3. Numerical Methods for Calculating the Aeroelastic Response and Stability of Rotor Blades in Forward Flight

A detailed description of this research can be found in Refs. 4-6, in particular the comprehensive review of this subject presented in Ref. 6, is important for overall understanding of this topic. In this research the aeroelastic stability and response problem of the coupled flap-lag-torsional dynamics of an isolated hingeless rotor blade in forward flight was considered. Linear quasi-steady aerodynamics below stall was included. The spatial dependence of the partial differential equations of motion was discretized using a multimodal Galerkin method, the resulting equation are nonlinear ordinary differential with periodic coefficients. Numerical treatment of such equations is difficult, and techniques for dealing with these equations are not available. Therefore a major accomplishment of this research was the development of a numerical scheme capable of determining the response and stability of nonlinear periodic systems.

The two basic problems which have precluded the convenient treatment of rotary-wing aeroelastic problems, in previous research, are twofold: (a) The time dependent nonlinear equilibrium position about which the aeroelastic perturbation equations are linearized is determined from the trim, or global equilibrium consideration, of the complete vehicle. Thus the aeroelastic and flight mechanics problems are intimately linked and (b) This nonlinear equilibrium position requires an exact solution of a nonlinear periodic system.

The numerical techniques developed in Ref. 4 enable one to calculate the trim state by solving a linear periodic response problem. Subsequently this method is combined with quasilinearization and applied iteratively to yield the "exact" nonlinear equilibrium state. Writing linearized perturbation equations about this nonlinear periodic blade equilibrium state enables one to determine the stability margins of the blade in forward flight, by using conventional Floquet theory.

The method described in Refs. 4 and 5 yields both the response and stability of the blade, at a particular advance ratio in 35 seconds of CPU time on an IBM 3033. The method is numerically an order of magnitude more cost effective than direct numerical integration schemes being used in the helicopter industry. Furthermore the method provides information on blade stability as well as information on the physical importance of the geometrically nonlinear terms, due to moderate blade deflections. These important items, which provide physical insight to blade dynamics, can not be obtained from the direct integration of the equations of motion.

The most important conclusions obtained in this study were:

- The numerical methods developed provide a very effective means for determining both aeroelastic stability and response. Quasilinearization provides a clear indication of the cases when nonlinear terms due to moderate deflections are important. The results indicate clearly that these terms can be both stabilizing and destablizing.

- Forward flight seems to be stabilizing the blade for a considerable number of cases considered, particularly when the blade is soft-in-plane. Severe degradation in stability with forward flight was observed only for the stiff-in-plane hingeless blade.

- The nonlinear time dependent, periodic equilibrium can significantly affect blade stability. Thus, for forward flight system stability is strongly coupled with the trim state.

- Comparison of coupled flap-lag-torsional analyses with coupled flap-lag analyses indicate that flap-lag analyses can underpredict damping levels in the in-plane mode quite severely. Thus, conclusions pertaining to blade behavior based on flap-lag analyses might be unreliable.

Finally it should be noted that in addition to the extensive documentation of this research which is already available (Refs. 4-6), a comprehensive report is also in preparation (Ref. 9). It is expected that this document will become available in the first half of 1983.

4. Formulation of the Helicopter Air Resonance Problem in Hover with Active Controls

This research, described in detail in Ref. 7, presented the derivation of a set of governing ordinary differential equations for a coupled helicopter rotor/fuselage system in hover. The objective is to model the air resonance aeromechanical instability of a helicopter in hover.

The rotor modelled is an N-bladed hingeless rotor. Each of the blades has flap, lag, and torsion elastic degrees of freedom. The blades can have pitch bearing offset, precone, pretwist, and offsets between the elastic center, mass center, aerodynamic center, and tension center of the cross-section.

The fuselage is a rigid body with longitudinal and lateral translational degrees of freedom and roll and pitch rotational degrees of freedom. Enforcing force and moment equilibrium as well as compatibility at the rotor hub couples the rotor and fuselage.

The ability to introduce active control of the rotor with the intent of eliminating the air resonance instability is included in the formulation.

The spatial dependence in the governing equations is eliminated by Galerkin's method. The final ordinary differential equations are presented as a set of nonlinear constant coefficient equations for the equilibrium state and a set of periodic coefficient linear perturbation equations, the perturbations about the nonlinear equilibrium state. Transforming the perturbation equations to a nonrotating rotor-plane coordinate system yields a set of constant coefficient equations with periodic forcing functions due to the active controls.

In this formulation the stability problem is reduced to a set of constant coefficient ordinary differential equations for which stability can be determined by a conventional eigenanalysis. The mathematical structure of this formulation also implies that air resonance instabilities can be suppressed by using linear control system theory.

It was the original intent of this research to investigate also the suppression of air resonance by using active controls. However due to the reduced funding level during the last year of the grant this objective could not be accomplished.

5. Optimum Design of Rotor Blades for Vibration Reduction in Forward Flight

This research was aimed at the aeroelastic tailoring of rotor blades for vibration reduction in forward flight and is described in detail in Ref. 8. Two papers, on this subject, are being written for presentation at two upcomming conferences (Refs. 10 and 11).

In this study modern structural optimization techniques were applied to vibration reduction of helicopter rotor blades in forward flight. The objective function minimized in the optimization study consists of the oscillatory vertical hub shears or hub rolling moments at one particular advance ratio. The behavior constraints are the frequency placements of the fundamental flap, lag and torsional modes of the blade and the requirement that aeroelastic stability margins, in hover, remain unaffected by the optimization process. Furthermore higher modes are constrained so as to avoid the four per rev resonances.

The structural load carrying, part of the blade cross section is represented by a thin walled single cell box. The dimensions of the torque box, namely; height, breadth and the corresponding wall thicknesses are treated as design variables. However the ratios of the wall thicknesses to the height and width of the torque box, respectively, are linked. Seven spanwise stations are used to represent the elastic and inertia properties of the blade. The breadth b_s and the thickness t_h at these spanwise stations are treated as design variables. Elastic properties of the blade in bending and torsion as well as mass properties are expressed in terms of these design variables. Furthermore a nonstructural mass, or counterweight, is used as a tuning device for controlling blade frequency placement. The nonstructural masses at the three most outboard stations of the blade are also used as design variables, while the offsets of these masses from the cross sectional elastic axis are given parameters. Side constraints are also placed on these design variables, in form of upper and lower bounds to prevent the design variables from reaching impractical values during the optimization process.

The free vibration modes used in the aeroelastic stability and response analysis are calculated using the Galerkin type finite element method described in Section 2 of this document.

The objective function minimized is a mathematical expression representative of vertical hub shears and hub rolling moments. In the present study the maximum peak-to-peak value of the oscillatory hub vertical shears or oscillatory hub rolling moments due to flap-wise bending was used as the objective function. The hub shears and rolling moment are obtained by integrating the blade loads over the span of the blade, resolving the total forces and moments acting at the rotor hub in the nonrotating reference frame and summing over all four blades.

The aeroelastic response analysis, described in Section 3, is a crucial ingredient required for the evaluation of the hub shears and rolling moments, which yield the objective function. Similarly the aeroelastic stability analysis, described in Section 3, is crucial for determining the aeroelastic constraints, and for checking that the final design has adequate aeroelastic stability margins.

The sequence of unconstrained minimization techniques (SUMT) based on an extended interior penalty function formulation was used for the optimization algorithm. In order to reduce the computational cost involved in the functional evaluation of the behavior constraints and the objective functions, explicit approximations based on the second order Taylor series expansion, are constructed to represent these functions. The sequence of approximate problems are solved by the optimizer exactly.

The optimization problem for a stiff-in-plane hingeless blade and two soft-in-plane blade configurations were studied and numerous detailed results were presented in Ref. 8. The conclusion obtained in the course of this study are summarized below:

- Optimum structural design can reduce vibratory hub shears, in forward flight, by 15-40%. This reduction is achieved by relatively small modifications of the original design, which yield optimal frequency placement in flap, lag and torsion. It is important to note that this reduction is accomplished by analysis and design and does not require the addition of a complicated system, such as used in higher harmonic vibratory load alleviation devices.

- The optimization process should be based on a comprehensive aeroelastic analysis, simplified analyses can easily lead to overly optimistic vibration level reductions.

- Aeroelastic stability margins in hover, are adequate constraints, when dealing with the optimum design problem in forward flight.

- Use of nonstructural mass, added in the outboard segment of the blade and in the vicinity of the blade elastic axis, is a very useful device in reducing vibration levels.

- As a byproduct of the optimization, the optimized blade configuration is between 9-20% lighter than the initial uniform blade. This result is achieved without using blade weight as the objective function, in the optimization process.

- Use of the oscillatory hub shears at an advance ratio of $\mu = 0.30$ represents an acceptable objective function for the optimization process. Furthermore oscillatory hub rolling moments did not seem to be suitable for the role of objective function.

- Optimization of blade configurations at an advance ratio which is in the vicinity of an aeroelastic stability boundary offers very limited potential for vibration reduction. Because the geometrically nonlinear terms dominate the response for this case.

6. Concluding Remarks

During the course of this research powerful analytical techniques were developed which will enhance the design tools available to engineers working in the helicopter industry. Furthermore a state-of-the-art review paper on rotary-wing aeroelasticity (Ref. 6) was also generated under the grant. It is believed that this paper represents an important contribution to the field, since it provides clarification on a number of current issues in this field and thus will serve as a valuable point of departure for engineers and researchers working in this field.

During the course of this research one M.S. student (Josh Levin), two Ph.D. students (Friedrich Straub and P. Shanthakumaran) and one postdoctoral research scholar (Dr. S.B.R. Kottapalli) have received full or partial financial support from this grant. Two of these are employed in the helicopter industry, Dr. Straub is a dynamics engineer at Hughes Helicopters, and Dr. Kottapalli is a dynamics engineer at Sikorsky. Dr. Shanthakumaran has accepted a research position with General Motors Research Labs and J. Levin is a Ph.D. student in the Aeronautics Dept. of Stanford University. Since presently there is a shortage of well trained, high caliber, personnel in both rotary-wing aeroelasticity and the field of structural dynamics, it is believed that this training of scientific personnel to supply the manpower needs of the U.S. research establishment and helicopter industry represents a significant additional benefit from the research which has been conducted under the grant.

With the conclusion of the research program on Response Studies of Rotors and Rotor Blades with Application to Aeroelastic Tailoring sponsored by NASA Research Grant NSG-1578, it is apparent from the foregoing that the past four years have been fruitful. In addition to the measurable productivity presented by published research results, this program has helped provide intellectual stimulation and educational enrichment for the graduate students and postdoctoral research scholars affiliated with the program. It is our earnest hope that many of the new tools which have been developed by this research activity will significantly influence future analysis and design practices in the field of rotary-wing aeroelasticity and structural dynamics.

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References (List of Publications which have Originated or are in Preparation under NASA NSG-1578)

Published Reports and Papers

1. Friedmann, P.P. and Straub, F., "Application of the Finite Element Method to Rotary-Wing Aeroelasticity", Journal of the American Helicopter Society, Vol. 25, No. 1, January 1980, pp. 36-44.

2. Straub, F.K. and Friedmann, P.P., "A Galerkin Type Finite Element Method for Rotary-Wing Aeroelasticity in Hover and Forward Flight", Paper No. 15, Proceedings of the Sixth European Rotorcraft and Powered Lift Aircraft Forum, Bristol, England, September 1980, pp. 15.1-15.29, (also published in Vertica, The International Journal of Rotorcraft and Powered Lift Aircraft, Vol. 5, No. 1, pp. 75-98, January 1981).

3. Straub, F.K. and Friedmann, P.P., "Application of the Finite Element Method to Rotary Wing Aeroelasticity", NASA CR-165854, February 1982.

4. Friedmann, P.P. and Kottapalli, S.B.R., "Rotor Blade Aeroelastic Stability and Response in Forward Flight", Paper No. 14, Proceedings of Sixth European Rotorcraft and Powered Lift Aircraft Forum, Bristol, England, September 1980, pp. 14.1-14.33.

5. Friedmann, P.P. and Kottapalli, S.B.R., "Coupled Flap-Lag-Torsional Dynamics of Hingeless Rotor Blades in Forward Flight", Journal of the American Helicopter Society, Vol. 27, No. 4, October 1982, pp. 28-36.

6. Friedmann, P.P., "Formulation and Solution of Rotary-Wing Aeroelastic Stability and Response Problems", Paper No. 3.2, Proceedings of Eighth European Rotorcraft Forum, Aix-en-Provence, France, September 1982, pp. 3.2-1 through 3.2-58 (also published in Procedings of International Symposium on Aeroelasticity, Nuremberg, Germany, October 1981, pp. 218-251).

7. Levin, J., "Formulation of the Helicopter Air Resonance Problem in Hover with Active Controls", M.S. Thesis, Mechanics and Structures Department, University of California, Los Angeles, August 1981 (copy of this document has been provided to the funding agency).

8. Shanthakumaran, P. and Friedmann, P.P., "Optimum Design of Rotor Blades for Vibration Reduction in Forward Flight", NASA CR, submitted for publication to the granting agency, December 1982.

Reports and Papers in Preparation

9. Friedmann, P.P. and Kottapalli, S.B.R., "Coupled Flap-Lag- Torsional Aeroelsatic Stability and Response of Hingeless Rotor Blades in Forward Flight", UCLA Report in preparation, to be completed June 1983.

10. Friedmann, P.P. and Shanthakumaran, P., "Aeroelastic Tailoring of Rotor Blades for Vibration Reduction in Forward Flight", to be presented at the 25th Israel Annual Conference on Aviation and Astronautics, February 23-25, 1983.

11. Friedmann, P.P. and Shanthakumaran, ,P., "Optimum Design of Rotor Blades for Vibration Reduction in Forward Flight", Paper to be presented at the 39th Annual Forum of the American Helicopter Society, May 9-11, 1983, St. Louis, Mo.