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A Study of Aeroelastic and Structural Dynamic Effects in Multi-Rotor Systems with Application to Hybrid Heavy Lift Vehicles

Peretz P. Friedmann, Professor

Mechanical, Aerospace and Nuclear Engineering Department

School of Engineering and Applied Science

University of California

Los Angeles, California 90024

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Summary of Accomplishments for the Period 1981-1983 Under NASA Research Grant NAG 2-116, Title: "A Study of Aeroelastic and Structural Dynamic Effects in Multi-Rotor Systems With Application to Hybrid Heavy Lift Vehicles"

1. Introduction and Overview

Under NASA Research Grant NAG 2-116, which was initially funded on May 1, 1981 and expired on December 31, 1983 an aeroelastic model suitable for the study of aeroelastic and structural dynamic effects in multirotor vehicles simulating a hybrid heavy lift vehicle was developed and applied to the study of a number of diverse problems. The analytical model developed proved itself to be quite reliable and flexible and it is capable of modeling a number of aeroelastic problems, namely:

(a) isolated blade aeroelastic stability in hover and forward flight

(b) coupled rotor/fuselage aeromechanical problem in air or ground resonance

(c) tandem rotor coupled rotor/fuselage problems and

(d) the aeromechanical stability of a multirotor vehicle model representing a hybrid heavy lift airship (HHLA).

The model was used to simulate the ground resonance boundaries of a three bladed hingeless rotor model, including the effect of aerodynamic loads, and the theoretical predictions compared well with experimental results. Subsequently the model was used to study the aeromechanical stability of a vehicle representing a hybrid heavy lift airship, and potential instabilities which could occur for this type of vehicle were identified. The coupling between various blade, supporting structure and rigid body modes was identified. This research which represents the first fundamental study of aeroelastic behavior of a hybrid heavy lift vehicle in the technical literature, indicates that dynamic effects are of considerable importance in the design of such vehicles.

The various aspects of this research have been documented in a series of publication, Refs. 1 through Ref 4 (see list of references at the end of this report). It should be noted that for the sake of convenience Ref. 4 is attached as Appendix A of this report. The major thrust of this research was concentrated on the three topics which are listed below:

1. Derivation of a general mathematical model capable of modeling coupled rotor/fuselage aeromechanical problems in multirotor vehicles including hybrid heavy lift airships (Ref. 1)

2. Validation of the general mathematical model by applying it to obtain the aeromechanical stability boundaries of a three bladed hingeless rotor and comparison of the theoretical results with experimental data (Refs. 2 and 3)

3. Fundamental study of the aeromechanical stability of a multirotor vehicle model representing a hybrid heavy lift airship (HHLA), (Refs. 2 and 4).

The major accomplishments in these three subject areas are briefly summarized in the following sections. Finally some additional information is provided in the concluding section.

2. General Mathematical Model for Coupled Rotor/Fuselage Aeromechanical Problems in Multirotor Vehicles

A detailed description of this study can be found in Ref. 1. The Hybrid Heavy Lift Airship (HHLA) or Hybrid Heavy Lift Helicopter (HHLA) is a candidate vehicle for providing heavy lift capability. Potential applications of this vehicle are for logging, construction, coast guard surveillance and military heavy lift. This vehicle consists of a buoyant envelope attached to a supporting structure to which four rotor systems, taken from existing helicopters are attached. This configuration is described in a schematic manner in Fig. 1 of Appendix A of this report. To be able to model the structural dynamic and aeroelastic behavior of multi-rotor system a set of governing differential equations of motion, capable of modeling the dynamics of this hybrid aircraft was developed. The principal goal of the first portion of this study was to develop a simple, yet accurate, mathematical model for such a vehicle consiting of multiple rotor systems connected by an elastic interconnecting structure, thrusters, a buoyant hull, and an underslung weight. To study the basic aeroelastic problems which could be encountered in an HHLA type configuration, a typical simplified model of such a configuration, shown in Fig.2 of Appendix A was selected. The essential features of this configuration are (Ref. 1):

(a) A flexible supporting structure, connecting the two rotors, with bending stiffness in the vertical and horizontal plane, combined with torsional stiffness along its longitudinal axis.

(b) Two rotor systems capable of providing lift, each having an arbitrary number of blades, are attached rigidly to the ends of the flexible structure

(c) Two masses are attached to the ends of the flexible structure. These masses represent helicpoter fuselages.

(d) A slung load W_{un} is attached to the structure. This weight can move or can be locked in a fixed position with respect to the flexible structure.

(e) An envelope providing the buoyant lift, acting at its center of pressure, is attached to the structure

(f) Concentrated axial loads P_{TFI}, P_{TF2} simulate thrusters.

Using this model, the dynamic equations of motion for the combined system consisting of two rotors, flexible structure, buoyant envelope and load W_{un} were derived. The derivation consists of four basic ingredients: blade equations including the effects of support motions, equations for the flexible structure connecting the rotors, equations representing the forces and moments introduced by the envelope and finally a representation of the dynamics of the load W_{un}.

A detailed derivation of these equations and the related assumptions are described in detail in Ref. 1, and their treatment is beyond the scope of this report. However a few important aspects of this mathematical model are briefly described below.

The blades are modeled by a rigid, offset hinged, spring restrained equivalent blade model; thus both articulated and hingeless rotors can be modeled. Each blade has flap, lead-lag and torsional degrees of freedom geometrically nonlinear terms due to moderate deflections, are included in the blade equations of motion. Aerodynamic loads are represented by quasisteady aerodynamics, and each rotor is assumed to consist of three blades or more. The hub is assumed to have pitch and roll degrees of freedom combined with two translational degrees of freedom in a plane parallel to the plane of rotation. The interconnecting, flexible, supporting structure (Fig. 2, Appendix A) has three elastic degrees of freedom. The final equations are obtained using an ordering scheme. As stated in Section 1 these equations can be used to represent four problems, namely: (a) isolated blade aeroelastic stability in hover or forward flight (b) aeromechanical porblems such as air or ground resonance of a single rotor system coupled to a fuselage (c) aeromechanical problems of tandem rotor helicopters and (d) aeromechanical stability problems of multirotor hybrid heavy lift airships or vehicles

3. Validation of the General Mathematical Model

The validity of the equations of motion described in the previous section was verified by applying them to the aeromechanical stability problem of a single rotor helicopter in ground resonance. The theoretical results from the analytical model were compared with high quality experimental data obtained by W. Bousman at NASA Ames (see Section 4 of Appendix A). The analytical results were in good agreement with the experimental results indicating that the equations of motion for the coupled rotor/vehicle system are reliable. Sample results from this validation study (Ref. 3) are presented in Figs. 5 and 6 of Appendix A. Figure 5 presents the variation of the rotor and body frequencies with rotor speed of rotation Ω. Figure 6 presents the variation of damping in the lead-lag regressing mode, which exhibits an instability, as a function of the rotor speed Ω. These figures show that the analytical predictions are in good agreement with the experimental results. Finally it should be noted that many additional comparisons between theoretical and experimental data can be found in Ref. 3.

4. Aeromechanical Stability Analysis of a Multirotor Vehicle Model Representing a Hybrid Heavy Lift Airship (HHLA)

A typical hybrid heavy lift vehicle is shown in Fig. 1 of Appendix A. Clearly such a vehicle is quite different from conventional rotorcraft. It is well known that aeroelastic and structural dynamic considerations are of primary importance in the successful design of rotary-wing vehicles. The aeroelastic and structural dynamic behavior of HHLA type vehicles has not been considered in the technical literature to date. The main objectives of this research grant were aimed at developing a fundamental understanding of the aeroelastic and aeromechanical problems which can be encountered in a HHLA type vehicle.

The nonlinear equations of motion capable of modeling the dynamics of this coupled multi-rotor/support frame/vehicle system, described in Section 2 and Ref. 1, were used to study the aeromechanical stability of an HHLA type vehicle. Results of this study are presented in Ref. 2 and in Ref. 4, which is also attached as Appendix A of this report. The coupling between various blade, supporting structure and rigid body modes is identified. Furthermore, the effects of changes in buoyancy ratio (i.e., buoyant lift/total weight) on the dynamic characteristics of the vehicle are studied. Some of the salient features of this analysis and a concise summary of the major conclusions is also provided in this section.

The total number of physical degrees of freedom representing an HHLA type vehicle was 31. These consisted of 24 blade degrees of freedom, 4 rigid body degrees of freedom and 3 elastic degrees of freedom of the supporting structure. The details of the solution and the results are presented in Appendix A. The most important conclusions obtained in this study were

1. The rotor cyclic lead-lag modes couple strongly with the bending modes and the torsion mode of the supporting structure, as a consequence, the stability of the lead-lag modes is sensitive to changes in stiffness (or the natural frequencies) of the supporting structure in bending and torsion. Therefore the natural frequencies of the supporting structure must be designed so as to be well separated from the frequencies of the rotor lead-lag modes. This also emphasizes the importance of modelling the supporting structure with an adequate number of elastic modes.

2. The low frequency and high frequency lead-lag modes of the rotor and the torsion mode of the supporting structure undergo a change in their basic characteristics, as the torsional stiffness of the supporting structure is increased from a low value to a high value.

3. The lead-lag modes of the rotor are stable only when the torsional stiffness of the supporting structure has low or high values, for intermediate values of the torsional stiffness one of the lead-lag modes is unstable.

4. The body pitch mode is a pure damped mode.

5. The body roll mode is a damped oscillatory mode. However, as the buoyancy ratio is decreased, this mode becomes unstable.

6. The stability analysis of the coupled rotor/vehicle dynamics clearly illustrates the fundamental features of the aeroelastic stability of the rotor, coupled rotor/support system aeromechanical stability and the vehicle dynamic stability in longitudinal and lateral planes.

Furthermore, it should be mentioned that the analytical model developed in this study, for the aeromechanical stability study of an HHLA type vehicle, can be also applied to various other types of vehicles as indicated in Section 1 of this report. Finally it should be noted that the analytical model is capable of representing not only aeroelastic and aeromechanical problems but it is also suitable for investigating rigid body stability and control problems associated with these types of vehicles.

5. Concluding Remarks

During the course of this research very useful analytical models were developed which will enhance the design tools available to engineers working in the rotary-wing field. A version of the computer programs used to generate the results was provided to Dr. H. Miura from NASA Ames Research Center.

During the course of this research one M.S. student (Paul Blelloch) and one postdoctoral research scholar (Dr. C. Venkatesan) have received full or partial financial support from the grant. Paul Blelloch's, M.S. thesis (Ref. 5), was partially funded by the grant. Presently Mr. Blelloch is a Ph.D student, at UCLA, working in the dynamics and controls area. Dr. Venkatesan is still associated with UCLA. 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 "A Study of Aeroelastic and Structural Dynamic Effects in Multi-Rotor System with Application to Hybrid Heavy Lift Vehicles", it is apparent from the foregoing that the past two and a half years have been fruitful. In addition to the measurable productivity represented by published research results, this program has helped provide intelectual stimulation and educational enrichment for the graduate student and postdoctoral scholar affiliated with the program. It is our hope that the analytical tools developed by this research activity will influence future analysis and design practices in the field of rotary-wing aeroelasticity and structural dynamics.

Acknowledgement

The extremely valuable advice and support of the grant monitor Dr. H. Miura are gratefully acknowledged.

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2. Venkatesan, C. and Friedmann, P., "Aeroleastic Effects in Multirotor Vehicles, Part II: Method of Solution and Results Illustrating Coupled Rotor/Body Aeromechanical Stability", NASA CR report under review.

3. Friedmann, P.P. and Venkatesan, C., "Comparison of Experimental Coupled Helicopter Rotor/Body Stability Results with a Simple Analytical Model", Paper presented at the Integrated Technology Rotor (ITR) Methodology Workshop, NASA Ames Research Center, Moffett Field, California, June 20-21, 1983, (accepted for publication in the Journal of Aircraft)

4. Venkatesan, C. and Friedmann, P., "Aeromechanical Stability Analysis of a Multirotor Vehicle Model Representing a Hybrid Heavy Lift Airship (HHLA)", AIAA Paper No. 84-0987-CP, presented at the 25th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference, May 14-16, 1984, Palm Springs, California.

5. Blelloch, P., "Coupled Rotor/Fuselage Aeromechanical Stability of a Hingeless Rotor Helicopter in Hover", M.S. Thesis, University of California, Los Angeles, Mechanical, Aerospace and Nuclear Engineering Department, May 1984.

APPENDIX A: AIAA Paper 84-0987-CP