GROUND RESONANCE ANALYSIS USING A SUBSTRUCTURE MODELING APPROACH

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Abstract

A convenient and versatile procedure for modeling and analyzing ground resonance phenomena is described and illustrated. A computer program is used which dynamically couples differential equations with nonlinear and time dependent coefficients. Each set of differential equations may represent a component such as a rotor, fuselage, landing gear, or a failed damper. Arbitrary combinations of such components may be formulated into a model of a system. When the coupled equations are formed, a procedure is executed which uses a Floquet analysis to determine the stability of the system. Illustrations of the use of the procedures along with the numerical examples are presented.

Introduction

The mechanical instability due to the interaction of helicopter rotor and fuselage, commonly known as ground resonance, is a very important consideration in the design of rotorcraft. The classical analysis of this phenomenon by Coleman and Feingold[1] still forms the basis for many of the analyses performed at the present time. The evaluation of the mechanical stability characteristics of nonisotropic rotors, as may be due to a component malfunction or combat damage, cannot readily be determined by these techniques.

The Floquet transition matrix analysis was applied to lifting rotor stability by Peters and Hohenemser[2] and was shown to be a powerful tool for determining the stability of periodic systems. In 1974, Hammond[3] applied this technique to analyze the effect of an inoperative blade damper on ground resonance. In this analysis each rigid hinged blade is a separate dynamic entity and thus may have completely independent parameters. There are no limitations on isotropy of either the rotor or fuselage. The results of this study were quite revealing and demonstrated that certain other approaches to this problem were not completely satisfactory. Lengthy time integration procedures were shown to be difficult to interpret and a common approximation which averages the damping loss over the blades may be very nonconservative.

The Floquet theory has the general capability to determine the stability of any helicopter configuration, regardless of the number of blades, type of retention, blade positioning, number of rotors, fuselage flexibility, landing gear characteristics, ground characteristics (e.g., ice), damage to blades (mass, damping, stiffness) or landing gear, and the physical arrangement of rotors and other components. Given the periodic equations of motion, the stability may be determined.

A difficulty in this process is the determination of the equations of motion of a complex configuration. One possibility is to derive the equations for a specific physical system and write a program to evaluate the numerical coefficients. Another scheme would be to derive the equations for a complex system which includes options to allow the modeling of a broad range of configurations. Either of these tasks would be extensive and the future analysis of a configuration not previously provided for would involve a great deal of effort.

The purpose of this paper is to describe a procedure which provides a convenient means of assembling the equations of motion for a large variety of rotorcraft configurations prior to invoking a Floquet analysis. Illustrations of several applications are presented.

The Model Concept

The complete dynamic system to be analyzed is called a "model." A model is described as a coupled set of "components." Each component is considered to

Presented at the Rotorcraft Dynamics Specialists' Meeting, Moffett Field, CA, November 7-9, 1984

be represented by a set of second order differential equations of the form

$$M\ddot{X} + C\dot{X} + KX = F \quad (1)$$

where M, C, K, F are mass, damping, stiffness matrices, and a force vector. X is a vector of the displacements of the degrees of freedom. In the implementation to be described all matrix coefficients may be functions of time and the state vector. The degrees of freedom may be of any generalized form as long as the coupling to other components may be described as linear relationships between the degrees of freedom of the components.

The equations of the model formed from a set of components are of precisely of the same form as Eq. (1) where

$$M = \sum T_I^T M_I T_I$$

$$C = \sum T_I^T C_I T_I$$

$$K = \sum T_I^T K_I T_I \quad (2)$$

$$F = \sum T_I^T F_I$$

and where the subscript I refers to the I^{th} component. The transformation matrix T_I is time invariant and relates the degrees of freedom of component I to the degrees of freedom of the model:

$$X_I = T_I X \quad (3)$$

This transformation is identical to that of Hurty[4], but is used to couple any generalized coordinates and it is recognized that the coefficients in Eq. (2) need not be constant.

Computer Implementation

A convenient implementation of this concept is described in References 5 and 6. This program (DYSCO) has three main features: 1) a "technology library" which includes various component representations ("technology modules"); 2) a "data library" which contains specific sets of data to be used by the technology modules to compute the equation coefficients; and 3) the capability to automatically form the transformation matrices and to compute the equations of motion of any assembly of components (a "model").

The main advantage to the user is that he may obtain (and solve) the numerical equations of any combination of components with no mathematical deviation. Another advantage is that he may select the most appropriate mathematical representation for each component.

The remainder of this section is a brief description of the features of the program relevant to ground resonance analysis.

The Technology Library

Included in the technology library are various representations of component equations. These modules are given a four character name, each starting with the letter "C." Those relevant to this study are briefly summarized.

<u>CRR2 - Rigid rotor</u>. Up to nine rigid hinged blades with optional flap, lag, pitch degrees of freedom (rotating system). Up to six degrees of freedom of the hub (fixed system). Data required includes: specification of degree of freedom options; radius, offset, spring and damper rates; and all necessary mass parameters. Up to four rotors may be included in any model.

<u>CFM2 - Fuselage, modal</u>. Up to six rigid body and six coupled elastic modes. Automatic coupling to rotor hub(s) and degrees of freedom of other components. Data required includes: degree of freedom options; locations of c.g., rotor(s), attachments to other components, mode shapes, all necessary mass and inertia parameters and modal frequency and damping. Up to four of these components may be included in any model.

<u>CSF1 - Structure, finite element</u>. Constant M, C, K, F model. Up to 40 degrees of freedom. Data required includes: degree of freedom names and the coefficient matrices. This module may represent a fairly complex structure or a single spring. Any number of these components may be used in a model (maximum number of components in a model is 20).

<u>CLC1 - Linear constraint</u>. Allows the user to specify any linear relationships between degrees of freedom.

In addition to the component technology modules, the library contains solution algorithms which may be invoked after the equations are formed. The solution modules names start with "S." Several of interest are:

<u>SSF3 - Stability, Floquet</u>. This solution module uses periodic shooting to find the initial conditions which may lead to periodic equilibrium condition for a linear or nonlinear model equation under specified control conditions. It then perturbs about the equilibrium state to form the Floquet transition matrix and

performs eigenanalysis to determine stability of the system. Data required includes: period of integration, initial integration increment, parameters for accuracy test of integration.

STH3 - Time History. Performs a time history integration on the model equations. Data required includes: length of solution, integration increment, initial conditions.

SEA4 - Eigenanalysis. Performs an eigenanalysis on the constant M, K matrices of the model.

The Data Library

The data library contains data to be used in the formation of the model equations. When the data is input, it is automatically assigned a "data member" name (DM) which is the name of the technology module with which it is to be used. Also, an arbitrary "data set" name (DS) is supplied by the user. A data unit is uniquely identified by its DS/DM name.

A particular physical component is represented by the name of the component technology module and the DS name of the data, e.g.,

CRR2 ROT1

where the user had previously identified a set of input for CRR2 as "ROT1."

The data library contains other data member types. One is the DM = MODEL which contains a definition of a model including component names and associated data set names. The data set name is a "model name" supplied by the user. The model definition is described below.

Model Definition

The user may formulate a model by specifying the component module names and the appropriate data set names which have been included in the libraries. For some components a rotor or structure number is required. A sample model may appear as shown in Fig. 1.

MODEL TEST I

INDEX	COMP	NO.	DATA SET
1	CFM2	1	FUSELAGE
2	CSF1		PAYLOAD
3	CRR2	1	MAINROT
4	CSF1		MAINGEAR
5	CSF1	.	TAILGEAR
6	CRR2	2	TAILROT
7	CSF1		VIBABS

Fig. 1. Example of a model definition.

Models may be conveniently edited to delete, replace, insert, and add components.

RUN Command

The program is command driven (See Reference 6 for details). The command "RUN" causes the program to perform the following sequence of operations.

1) User is requested for the name of the model.

2) Model definition is retrieved from data library.

3) Each component module and data set is accessed to define degrees of freedom.

4) Transformation matrices are formed.

5) Each component module is accessed to form equation coefficients.

6) Coefficient matrices are transformed to system equations.

During this process, data is validated for existence and uniqueness and access is provided for computation of nonconstant coefficients.

After step 6, the user has options to print certain model details, such as degrees of freedom and constant system matrices. At the completion of the RUN command the user is requested to name a solution module to be executed.

Coupling

The coupling is carried out by an automatic procedure in which the names of the degrees of freedom are recognized and processed by the program. The degree of freedom names consist of two FORTRAN words, formatted A4, I4. Certain names are automatically formed, as for example

ZETA2300

which is interpreted as: lag angle, rotor 2, blade 3.

When the program recognizes the same name in more than one component, these degrees of freedom are automatically joined. Linear relationships between degrees of freedom are also automatically processed into the transformation matrices (See Reference 5).

As a simple illustration of an application of this coupling procedure to model a failed lag damper, consider a model which includes a rotor with lag dampers whose damping rates have been input as the numeric quantity, c. In order to represent a failed damper, the model is edited to add the following component.

CSF1 FAILDAMP

where the data set FAILDAMP contains the following information.

number of degrees of freedom = 1

name of degree of freedom = ZETA1100

M, K, F = null

C = -c

The addition of this component represents the addition of a negative damper on blade 1 of rotor 1 which cancels the original damping rate. No further action is required of the user except to execute the command RUN.

Examples and Discussions

In order to demonstrate the concepts described, several analyses have been performed which include: 1) comparison with the results of Hammond[3]; 2) Validation of a reduced model; 3) Coaxial rotor configuration; 4) Tandem rotor configuration. Throughout this study, the same rotor parameters are used which are based on the data of Reference 3. The parameters may not be realistic, but are used to illustrate the procedures described.

Table 1. Rotor parameters.

Number of blades	4	
Blade mass	6.5	slugs
Blade mass moment	65	slug-ft
Blade mass moment of inertia	800	slug-ft^2
Lag hinge offset	1	ft
Lag spring	0.0	ft-lb/rad
Lag damper	3000	ft-lb-sec/rad

It is noted that in the rotor component the blade degrees of freedom are in rotating system and hub degrees of freedom are in the nonrotating system. In the fuselage module components, all the degrees of freedom are in nonrotating system. Note also that the damaged blade is always referred to as blade 1.

The components used in this study, their associated data set names, and their characteristics are described as follows. They are used in various combinations in the examples below.

1) CRR2, ROTOR1 - 4 blades, inplane degrees of freedom (ZETA1100, ZETA1200, ZETA1300, ZETA1400), 2 hub translational degrees of freedom (XHUB1000, YHUB1000), counterclockwise rotation, various rotational speeds, 6 degrees of freedom (DOF).

2) CRR2, ROTOR2 - Same as 1) but clockwise rotation and DOF names are ZETA2100, ZETA2200, ZETA2300, ZETA2400, XHUB2000, YHUB2000.

3) CFM2, FUSELAGE - 5 rigid body modes (XCG 1000, YCG 1000, ROLL1000, PTCH1000, YAW 1000), automatically couples to rotor 1 and rotor 2, mass = 10000 lb., roll and pitch moments of inertia = 10000, 15000 slug-ft^2.

4) CLC1, REDUCE1 - Couples blades 2, 4 (ZETA1200 = -ZETA1400) and blade 1, 3 (ZETA1100 = -ZETA1300) of rotor 1.

5) CLC1, REDUCE2 - Couples blade 2, 4 (ZETA2200 = -ZETA2400) and blade 1, 3 (ZETA2100 = -ZETA1200) of rotor 2.

6) CLC1, RED124 - Couples blade 2, 4 (ZETA1200 = -ZETA1400) of rotor 1.

7) CLC1, RED224 - Couples blade 2, 4 (ZETA2200 = -ZETA2400) of rotor 2.

8) CLC1, COAX - Couples hub degrees of freedom of rotor 1 and rotor 2 to form coaxial rotor (XHUB1000 = XHUB2000, YHUB1000 = YHUB2000).

9) CSF1, LDGEAR - Equivalent damper and spring rate at fuselage CG of landing gear system, 5 DOF (XCG 1000, YCG 1000, ROLL1000, PTCH1000, YAW 1000), null mass matrix, diagonal damping matrix = [3500, 1750 lb-sec/ft, 8333, 16666, 16666 ft-lb-sec/rad], diagonal stiffness matrix = [168000, 168000 ft/lb, 250000, 666666, 666666 ft-lb/rad].

10) CSF1, DAMPFAL1 - Failed damper of blade 1 of rotor 1, 1 DOF (ZETA1100), null mass, stiffness matrices, damping matrix = [-3000 ft-lb-sec/rad].

11) CSF1, DAMPFAL2 - Same as CSF1, DAMPFAL1 but DOF = ZETA2100.

12) CSF1, HUBNON - Nonisotropic hub, 2 DOF (XHUB1000, YHUB1000), diagonal mass matrix = [552.8, 225 slug], diagonal damping matrix = [3500, 1750 lb-sec/ft], diagonal stiffness matrix = [8500, 8500 lb-ft].

13) CSF1, HUBISO - Isotropic hub, 2 DOF (XHUB1000, YHUB1000), diagonal mass matrix = [552.8, 552.8 slug], diagonal damping matrix = [3500, 3500 lb-sec/ft], diagonal stiffness matrix = [85000, 85000 lb/ft].

Comparison and Validation

Four cases have been used to compare results of this study and those of Reference 3. The first case is described as an isotropic rotor on an isotropic hub in Reference 3.

The corresponding DYSCO model is shown in Fig. 2.

MODEL II

INDEX	COMP	NO.	DATA SET
1	CRR2	1	ROTOR1
2	CSF1		HUBISO

Fig. 2. Model definition for an isotropic rotor on an isotropic hub.

The details of each component can be seen in the previous sections, 1) and 13). Note that the matched degree of freedom names in these two components is all that is needed to dynamically couple them.

The second case is a nonisotropic rotor on an isotropic hub and the corresponding model is shown in Fig. 3.

MODEL NI

INDEX	COMP	NO.	DATA SET
1	CRR2	1	ROTOR1
2	CSF1		HUBISO
3	CSF1		DAMPFAL1

Fig. 3. Model definition for a nonisotropic rotor on an isotropic hub.

Model NI is constructed by simply adding the component, CSF1, DAMPFAL1, which contains the negative damping rate of the rotor blade lag damper and makes the damping rate of the first blade equal to zero.

If component CSF1, HUBISO is replaced by CSF1, HUBNON, in Model II and NI, then Model IN and NN are obtained which correspond to an isotropic rotor on a nonisotropic hub and a nonisotropic rotor on a nonisotropic hub, respectively.

Each of the above models was formed and the Floquet stability analysis, SSF3, was executed. The results are shown in Figs. 4-7. In these figures, the circles represent the results from Reference 3 and the crosses are the results of the present study. As can be seen, the agreement is generally excellent and the validity of the techniques described is verified.

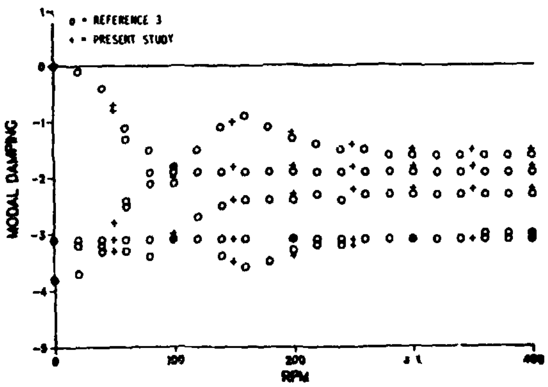

Fig. 4. Modal damping of an isotropic rotor on an isotropic hub.

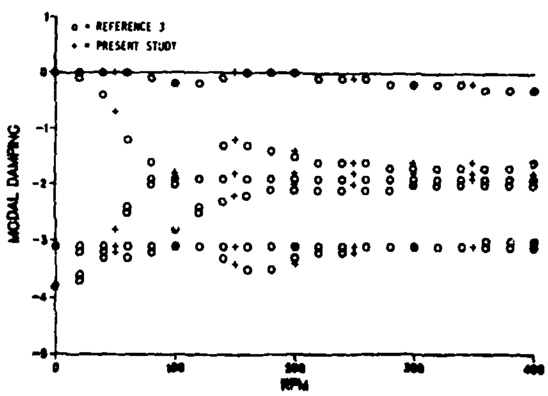

Fig. 5. Modal damping of a nonisotropic rotor on an isotropic hub.

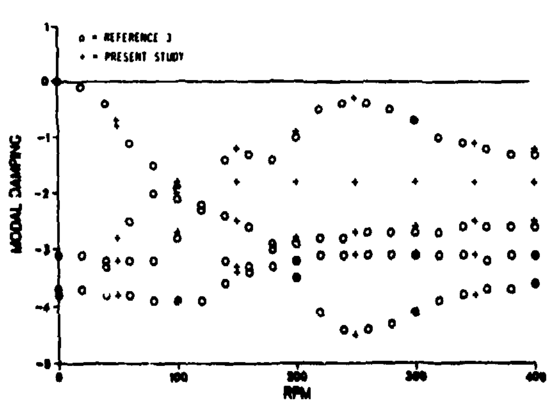

Fig. 6. Modal damping of an isotropic rotor on a nonisotropic hub.

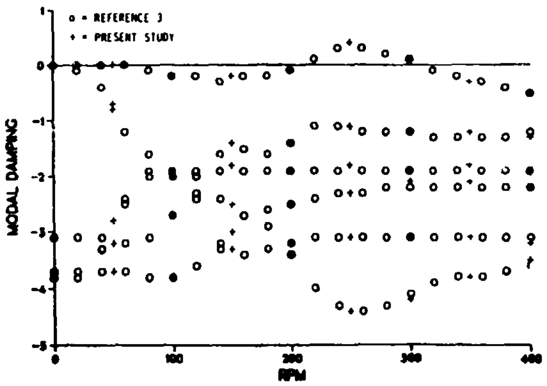

Fig. 7. Modal damping of a nonisotropic rotor on a nonisotropic hub.

Reduced Model

Eigenanalyses are often quite sensitive to multiple or close roots. Higher precision and greater computational time may be required and sometimes a failure to converge condition may arise for a highly isotropic configuration. In order to make the problem less complicated, numerically more stable, computationally more efficient and easier to interpret, it would be desirable to remove any unnecessary degrees of freedom. Consider the method of multiblade coordinates. The motion of the mass center of an isotropic rotor is proportional to the first order cyclic motion of the multiblade coordinates.[7] For the ground resonance phenomena, it is the motion of the mass center of the blades coupling with hub translational degrees of freedom that produces the instability. For this reason only two degrees of freedom have to be considered for an isotropic N-bladed rotor. For a damage analysis, however, the above-mentioned technique fails. For an N-bladed anisotropic rotor even when one transforms the blade degrees of freedom to a multiblade coordinate system, it is necessary to retain all the degrees of freedom.

In the present study, the blade degrees of freedom are in the rotating system. For a four-bladed isotropic rotor two degrees of freedom can be removed by satisfying two constraints: ZETA1300 = -ZETA1100, ZETA1400 = - ZETA1200. If blade one is damaged, there is still one degree of freedom that can be removed by setting ZETA1400 = -ZETA1200. The reasoning is as follows. For an even number of identical equally spaced blades, one may describe the motion by modes representing the sum and differences of the motions of opposite blades. The mode representing the sum of the motions does not contribute to the hub shear force. Therefore, for pairs of opposite identical blades, only equal and opposite motions need be considered. However, if these two blades are not identical then both modes contribute to the hub shear force.

Although the above-mentioned modes have no contribution to hub shear forces, when the hinge offset is not zero these modes can produce a yaw moment acting on the shaft. This, in turn, may affect the hub displacement through the coupling among fuselage degrees of freedom. In general, however, this effect should be very small.

Two cases used in the last section (Models NI, NN) were used to validate the reduced model. The action required was to add one more component, CLC1, RED124 to the original models. The function of this component is to constrain the motion of blades 2 and 4 to reduce the total system degrees of freedom. The reduced models are shown in Figs. 8 and 9.

MODEL REDUNI

INDEX	COMP	NO.	DATA SET
1	CRR2	1	ROTOR1
2	CSF1		DAMPFAL1
3	CSF1		HUBISO
4	CLC1		RED124

Fig. 8. Reduced model of nonisotropic rotor on isotropic hub.

MODEL REDUNN

INDEX	COMP	NO.	DATA SET
1	CRR2	1	ROTOR1
2	CSF1		DAMPFAL1
3	CSF1		HUBNON
4	CLC1		RED124

Fig. 9. Reduced model of nonisotropic rotor on nonisotropic hub.

The results of the Floquet stability analyses are shown in Tables 2 and 3. They illustrate that the reduced model is a good representation of the original model and that the reduced degree of freedom may be decoupled from the system. Note that the missing modes in these tables must always be stable, based on the previous discussion. In addition to the results shown in Tables 2 and 3, other tests have also been conducted for more complicated models, some of them will be shown below, which further confirm the validity of the reduced model.

Table 2. Eigenvalues of a nonisotropic rotor on an isotropic hub and its reduced model.

RPM = 175			
MODEL NI		MODEL REDUNI	
FREQUENCY	DAMPING	FREQUENCY	DAMPING
±5.36324	0.04882	±5.36309	0.04881
±5.03417	-1.30844	±5.03401	-1.30847
±4.82731	-1.78823	XXXXXXX	XXXXXXX
±5.86593	-2.04050	±5.86574	-2.04051
±6.55204	-3.05332	±6.55204	-3.05332
±6.79967	-3.46174	±6.79963	-3.46170

Table 3. Eigenvalues of a nonisotropic rotor on a nonisotropic hub and its reduced model.

RPM = 225			
MODEL NN		MODEL REDUNN	
FREQUENCY	DAMPING	FREQUENCY	DAMPING
±6.68678	0.20268	±6.68678	0.20268
±6.39124	-1.06817	±6.39124	-1.06817
±6.37237	-1.78824	XXXXXXX	XXXXXXX
±8.88663	-2.30105	±8.88663	-2.30105
±11.77885	-3.12293	±11.77885	-3.12293
±6.69736	-4.10262	±6.69736	-4.10262

Coaxial Model

A reasonable coaxial model can be easily obtained based on rotor and hub data used in the previous section. The definition of such a model is shown in Figure 10.

MODEL COAXIAL1

INDEX	COMP	NO.	DATA SET
1	CRR2	1	ROTOR1
2	CRR2	2	ROTOR2
3	CSF1		HUBNON
4	CSF1		HUBNON
5	CLC1		COAXIAL

Fig. 10. Model definition for coaxial, nonisotropic hub configuration.

As can be seen in Fig. 10, two counter rotating rotor components are used. Component CLC1, COAXIAL is used to couple the hub degrees of freedom of these two rotors. Component CSF1, HUBNON is used twice to double the mass, damping rate, and spring rate of the nonisotropic hub used in the single rotor model.

To consider the case with one damper inoperative, one simply adds component CSF1, DAMPFAL1, as shown in Fig. 11.

MODEL COAXIAL2

INDEX	COMP	NO.	DATA SET
1	CRR2	1	ROTOR1
2	CRR2	2	ROTOR2
3	CSF1		HUBNON
4	CSF1		HUBNON
5	CLC1		COAXIAL
6	CSF1		DAMPFAL1

Fig. 11. Model definition for coaxial configuration with failed damper.

The unimportant degrees of freedom may be removed as described earlier by adding two components as shown in Fig. 12.

MODEL COAXIAL3

INDEX	COMP	NO.	DATA SET
1	CRR2	1	ROTOR1
2	CRR2	2	ROTOR2
3	CSF1		HUBNON
4	CSF1		HUBNON
5	CLC1		COAX
6	CSF1		DAMPFAL1
7	CLC1		RED124
8	CLC1		REDUCE2

Fig. 12. Reduced model for coaxial configuration with failed damper.

To model failed dampers in both rotors, model COAXIAL4 may be formed as in Fig. 13.

MODEL COAXIAL4

INDEX	COMP	NO.	DATA SET
1	CRR2	1	ROTOR1
2	CRR2	2	ROTOR2
3	CSF1		HUBNON
4	CSF1		HUBNON
5	CLC1		COAXIAL
6	CSF1		DAMPFAL1
7	CLC1		RED124
8	CLC1		RED224
9	CSF1		DAMPFAL2

Fig. 13. Model for coaxial configuration with two failed dampers.

Fig. 14 shows the modal damping of the least stable mode of model COAXIAL2 and its reduced model COAXIAL3. It is seen that these two models show exactly the same damping ratio. As compared with the result with those of the corresponding single rotor model (model NN), in the unstable region, the instability is less severe for model COAXIAL3, as is to be expected. The case with two dampers damaged can be seen in Fig. 15. It is interesting to see that there are two unstable modes in this case. The eigenvector of the mode indicated by 1 in the figure shows that this mode is primarily due to the coupling among hub translational degrees of freedom and the two damaged blades. That is why the damping ratio remains nearly constant as rotating speed is changed. The second mode, however, is the ordinary coupled hub-inplane unstable mode.

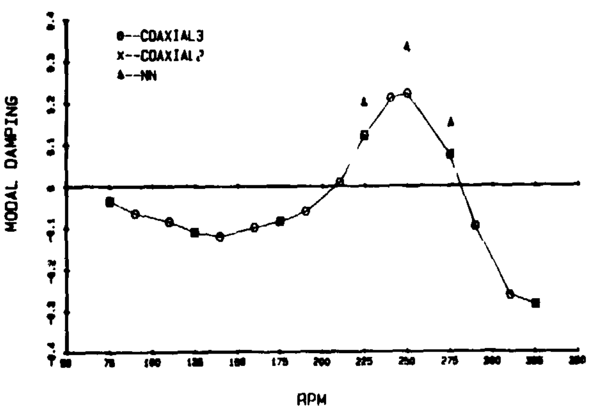

Fig. 14. Damping of the least stable mode of model COAXIAL2 and its reduced model COAXIAL3.

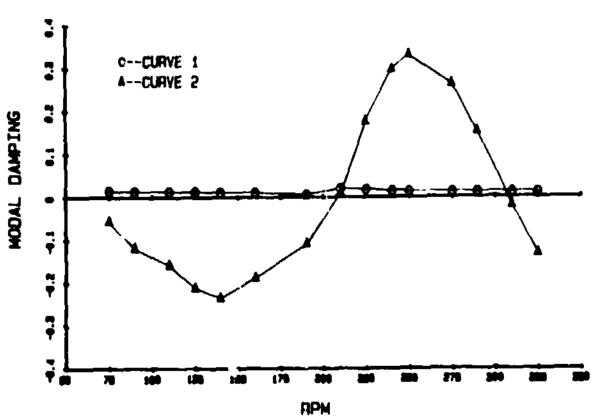

Fig. 15. Damping of two least stable modes of model COAXIAL4.

Tandem Model

Fig. 16 illustrates a model of a tandem helicopter.

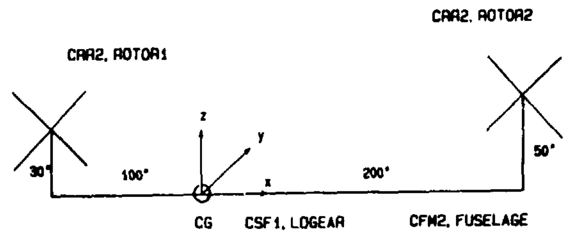

Fig. 16. Geometric configuration of tandem helicopter.

The data used in this simulation may not be realistic but the main purpose is to illustrate the modeling procedures and the convenience of the substructure modeling approach. The rotor hub and landing gear degrees of freedom are coupled with the fuselage rigid body degrees of freedom automatically by the naming convertion. The model definition is shown in Fig. 17.

MODEL TANDEM

INDEX	COMP	NO.	DATA SET
1	CRR2	1	ROTOR1
2	CRR2	2	ROTOR2
3	CFM2	1	FUSELAGE
4	CSF1		LDGEAR
5	CLC1		REDUCE1
6	CLC1		REDUCE2

Fig. 17. Model definition for TANDEM.

The model with one damper failed is TANDFAIL and depicted in Fig. 18.

MODEL TANDFAIL

INDEX	COMP	NO.	DATA SET
1	CRR2	1	ROTOR1
2	CRR2	2	ROTOR2
3	CFM2	1	FUSELAGE
4	CSF1		LDGEAR
5	CLC1		RED124
6	CLC1		REDUCE2
7	CSF1		DAMPFAL1

Fig. 18. Model definition for TANDFAIL.

The two unstable modes of this vehicle are shown in Fig. 19. The eigenvector of mode 1 reveals that it is primarily a coupled yaw, pitch, and lag mode. Mode 2, on the other hand, is due primarily to the coupling of fuselage translational degrees of freedom and in plane motion of the blade. It is also demonstrated in Fig. 19 that the instability is more severe when one blade damper is inoperative.

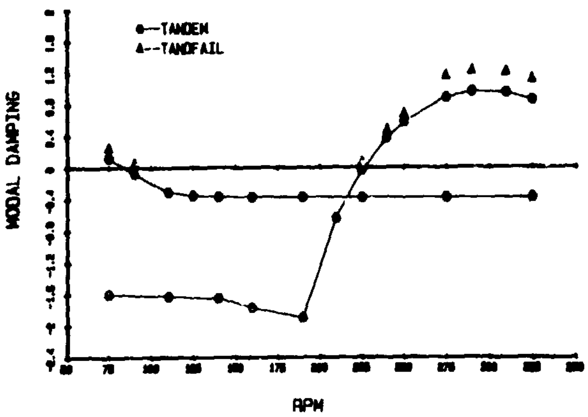

Fig. 19. Damping of the two unstable modes of tandem model.

Conclusion

The purpose of the paper was to illustrate the convenience and versatility of a procedure for ground resonance analysis through a general substructure synthesis procedure.

The ease of modeling failed dampers on conventional, coaxial, and tandem helicopters has been demonstrated.

The accuracy of the procedure has been illustrated by comparing the results with a previous analysis.

The ability to conveniently evaluate a theoretical concept (which reduces the blade degrees of freedom) has also been demonstrated.

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DISCUSSION*
Paper No. 2

GROUND RESONANCE ANALYSIS USING A SUBSTRUCTURE MODELING APPROACH

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and
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Peretz Friedmann, University of California, Los Angeles: I have a couple of questions so let's start with the first one. The test with which you are currently correlating DYSCO results with Hammond's analysis is a very good way to go. However, I was wondering why you didn't try to correlate the ability of this code to predict ground resonance with experimental data which Bill Bousman obtained and which Friedrich Straub showed in one of his slides at the beginning. That's a better test for the problem and a lot of ITR comparisons have been done with that particular case. If the DYSCO program could reproduce these results, it would be a good verification of the code.

Austin: Yes, I would like to do that. Actually this paper was prepared entirely extracurricularly. Not a part of any given job description. We took the expedient approach of going with Hammond's results. We felt that it was a pretty good verification of our implementation, not of the physical model, of which components we had, because we were correlating with actually three different methods of calculation. We would like to do some correlation with actual test data also.

Friedmann: The second question I have is more along the lines of a comment. When you started describing DYSCO on the right hand side of the equations you will remember you had left all the nonlinear terms in the constraints for F_C. The problem I have with these equations is that I am not convinced that it has the capability of dealing with the nonlinear effects which might be important. The correlation you have run is for a ground resonance problem where everything is always linear. I would suggest that one of the future endeavors is to look at the problem where nonlinear effects [could be important].

Austin: No question.

Jing Yen, Bell Helicopter: I have a very general question for you or for all of you. For thirty years we've been working very hard to prevent the ground/air resonance problem. The technical community has been working very hard to improve our prediction capabilities. From your point of view, right now, how much confidence level do we have in the prediction techniques? How much confidence level do we have now? In other words in the next ten years, when we have our Third Decennial Meeting here will we still be talking about the same thing again? How much confidence do we have right now versus the way we were ten years ago? This is an open question.

Austin: Well, personally, my confidence has not been real high because so often the data we have been getting from you folks has been in terms of equivalent hub impedance. We would get a scrambling of numbers--one is for a landing gear failed, another one is for ice. I've never really been able to find out from you where those numbers came from. Also, of course, these numbers are very directly related to the rotor rpm and it has never been especially clear in the material I have received in evaluations that you have actually gotten experimental data at the right rpm for these impedances. So my confidence has been pretty low. I think if we can move to a point where we have more descriptive models and then can verify their correlation with some flight test data that we ought to be able to put this thing to rest.

Jerry Miao, Sikorsky Aircraft: I heartily agree with your [comment] about getting those spring rates. [They are hard to come by--stiffness values for ground contact, concrete, turf, ice, landing gear and so forth.] They are difficult to get. But I draw a different conclusion. My conclusion is that our analysis capability is pretty good. We can predict ground resonance if we know how to put those numbers into it. Therefore, in the aircraft shake test normally we do a ground resonance test to determine where the ground roll mode is or pitch mode is. [We can find those numbers, but] finally, what is the tire stiffness, the oleo stiffness, or the ground surface contact stiffness.

Austin: I think the Army will probably continue to use analysis to try to identify the most critical cases. I don't think the industry is ever going to get away from the requirement of

*The transcript of this discussion is incomplete because of recording problems. Areas of ambiguous or missing text have been discussed with the person asking or answering the question and the text is indicated with brackets.

actually demonstrating those critical cases, even though it may mean bringing in blocks of ice on a hot summer day or whatever.

Bob Sopher, Sikorsky Aircraft: The type of blade that you used here, was it a non-elastic blade?

Austin: Yes, it was. That was a matter of choice. We're working on a representation of more complex blade elasticity models. It will then be just a matter of basically selecting one or the other and putting in some modal data for the blades.

Sopher: So that the elastic blade is not yet available?

Austin: No, but it will be very shortly according to the last schedule submitted to the Army. It may actually in fact be a little longer than that.

Sopher: Well, that may explain why you haven't tried to correlate with the Bousman data base on hingeless rotors.

Austin: Right. You would have to use equivalent springs if you were going to do it right now.

Benson Tongue, Georgia Institute of Technology: My question is substructure modeling [decreased the cost] of the technique and so I was curious about that. What is the relative content of your cost [for calculations using Floquet analysis, modal analysis, and so forth?]

Austin: The cost of the cases we ran for our machine was inconsequential. I'm not sure, it may have been ten times zero or twenty. That isn't a factor at all for us in the Army. It's your tax dollars at work. No, really the solution does not take much time so I don't think it would be a major obstacle for most folks. Alex, do you want to address that?

Alex Berman, Kaman Aerospace: Yes. Actually there is no [particular special cost in running DYSCO.] What you should have to do is compare the computational costs against the cost of developing specific models [for a new configuration and modifying the appropriate code.]

Euan Hooper, Boeing Vertol: I was going to ask is DYSCO in the public domain? I see that it was published last year at [the 24th SDM, Lake] Tahoe, but is the FORTRAN coding available in the public domain?

Austin: That's a tricky question. Our contract that Alex is working on now calls for the program itself to be in the public domain. The source code for the Executive will, however, be delivered in a binary form rather than a FORTRAN source. So you can't make changes to the Executive, but all the technical modules will be supplied and you can add technical modules without reference to that Executive.

Hooper: And when will this system be available?

Austin: Make a new guess, Alex.

Berman: A few months or so.

Austin: Personally, I would like to encourage everybody to write me a letter and ask for it. I'm hoping that we will be able to do ground resonance analysis using it in future acquisitions of interest.

Hooper: If I could just add. We've got some experience with using government programs. I would like to emphasize that you don't shortcut the documentation process. Anything you can do to not only document it well but annotate the coding. Please, do what you can, but don't shortcut the process.

Austin: We try to encourage our contractors to do that. Some of you do it better than others. But I think the documentation will be good for DYSCO.