CUMENTATION PAGE

Form Approved
OMB No. 0704-0188

2

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE Nov 92

3. REPORT TYPE AND DATES COVERED Final 1 Dec 88 - 30 Sep 92

4. TITLE AND SUBTITLE
Stability of Elastically Tailored Rotor Systems

5. FUNDING NUMBERS
DAAL03-89-K-0007

6. AUTHOR(S)
Dewey H. Hodges, Lawrence W. Rehfield
Mark V. Fulton

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Georgia Institute of Technology
Atlanta, GA 30332-0150

DTIC
ELECTE
FEB 18 1993
S B D

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 25327.6-EG

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

93-03044

10P8

13. ABSTRACT *(Maximum 200 words)*

In this work the objectives included (1) the development of models and analysis methodology for rotor stability in hover, incorporating all relevant nonclassical structural effects; (2) the validation of the models and analysis methodology, including convergence; and (3) the conduct of limited design studies with the tools developed in order to enhance understanding of the role of elastic couplings on stability. All these objectives were met. The final report contains a brief summary description of the results of the work. Details may be found in the published papers listed at the end of the report.

14. SUBJECT TERMS
Rotor Systems, Laminated Composites, Rotor Stability, Rotor Blades, Rotor Blade Stability, Composite Materials

15. NUMBER OF PAGES 9

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

Stability of Elastically Tailored Rotor Systems

Dewey H. Hodges, Lawrence W. Rehfield, and Mark V. Fulton

Final Technical Report

1 December 1988 – 30 September 1992

November 30, 1992

Research Supported by the U.S. Army Research Office

Contract DAAL03-89-K-0007 (ARO Proposal Number: 25327-EG)

Principal Investigators: Dewey H. Hodges and Lawrence W. Rehfield[1]

Grant Monitor: Dr. Gary L. Anderson

Georgia Institute of Technology
School of Aerospace Engineering
Atlanta, Georgia 30332-0150

---

[1] Presently with the University of California at Davis

Introduction

Background

A significant attribute of laminated composites is their design flexibility. The layers or plies of a laminate are, in fact, modular units which can be selected to provide distinct material properties and fiber orientations. It is possible, therefore, to tailor the properties of composites to meet specific design requirements. Relatively little work has been done to apply principles of aeroelastic tailoring to rotor blades. Rotor blades must satisfy strength, weight, frequency, and lifetime requirements; and aeroelastic instabilities must lie outside the flight envelope. The primary issue when it comes to design of composite rotor blades is the overall suitability of tailored blades for practical applications.

It is well known that elastic couplings can have a strong influence on rotor blade stability. Thus, any attempt to utilize the couplings of composite materials in rotor blade design must include a concomitant investigation of the influence of the coupling on stability. One possibility for utilizing tailoring in rotor system design is based upon the creative use of extension-twist coupling to achieve enhanced performance. This and other uses have strong potential for breakthroughs in design methodology.

Objectives

In this work our objectives included (1) the development of models and analysis methodology for rotor stability in hover, incorporating all relevant nonclassical structural effects; (2) the validation of the models and analysis methodology, including convergence; and (3) the conduct of limited design studies with the tools developed in order to enhance understanding of the role of elastic couplings on stability. We believe that all these objectives were met. What follows is a brief summary description of the results of our work. Details may be found in the published papers listed at the end of the report.

Unique Features of Work

New Models and Analysis Methodology The aeroelastic stability analysis of composite blades should be performed as a two-stage operation for the best combination of computational efficiency and accuracy. The first step is to *determine* blade cross-sectional stiffnesses. This can be done either by means of simplifying the analytical model so that the stiffnesses can be determined in closed form or by applying powerful dimensional reduction techniques to the three-dimensional representation, which leads to a two-dimensional finite element solution for the stiffnesses and a corresponding set of one-dimensional (global or beam) equations. The second step is to *use* the sectional stiffnesses and the corresponding beam equations to conduct an aeroelastic analysis of the rotor blade, obtaining measures of the global dynamic behavior of the blade such as frequencies and mode shapes without aerodynamics or stability eigenvalues with aerodynamics. An optional third step is to substitute the results from the global analysis back into approximate three-dimensional recovery relations to get pointwise asymptotically correct approximations of displacement, strain, and stress. For simplicity, this third step was not undertaken in our work.

In the course of our work several sectional analysis methods were developed, adopted, and studied. Analyses developed include one based on potential energy and another based on complementary energy by Dr. Rehfield. Codes that were adopted and studied include Marco Borri's code NABSA, based on Giavotto et al. (1983); Mark Nixon's code TAIL based on

Rehfield (1985); Carlos Cesnik's code VABS, based on the work of Hodges et al. (1992); and a code based on the work of Badir (1992). These codes were used because they have been shown to be accurate and they were available at the time we needed them.

The global beam equations of motion are those of Hodges (1990) and are solved directly from the mixed variational statement developed therein. Our stability analysis was formulated from this variational statement with simple mixed finite element shape functions. The finite element shape functions are the crudest possible based on the variational statement which is in the "weakest possible form." For example, all the unknown field variables are represented as piecewise constant within the element. This allows for exact element quadrature by inspection. The resulting coefficient matrices are extremely sparse, and taking advantage of that sparsity leads to a very efficient computational scheme for the nonlinear equlilibrium solution, which runs on workstations in a few minutes.

The resulting aeroelastic stability analysis code, STAB, accounts for all possible material elastic couplings and uses an aerodynamic model similar to that of GRASP (developed at the Aeroflightdynamics Directorate). *Mathematica* (a computerized symbolic manipulator) was used to write extensive portions of the code. STAB is capable of solving for the equilibrium deflections of a rotating blade and linearized dynamics of small motions about equilibrium for the hovering flight condition. Both of these solutions are needed for stability analysis.

Validation Studies The analyses developed under this grant were thoroughly validated. The types of validation include linear and nonlinear static deflection of isotropic and composite beams, free-vibration frequencies and modes for nonrotating isotropic and composite beams, and modal damping for hingeless rotors made of isotropic and composite materials. While not exhaustive, these sorts of validation studies ensure that all structural effects are represented accurately. These validation studies were done in an incremental fashion in order to gain confidence in each part of the analysis and code. In every case our results are at least as good as published results, and in most cases they are noticeably better. In validation of the large-deformation characteristics of composite beams, for example, we were able to calculate stiffness properties from "first principles" producing deflections which agreed with experiment much better than existing theories. We also validated our finite element code against our transfer matrix code. Note that the transfer matrix method is capable of calculating the frequency of each mode with comparable accuracy, whereas the finite element results deteriorate as the number of the mode increases. Thus, if the discussion is restricted to the lower-frequency modes, the finite element results can be used with confidence. As part of the validation, we also determined the convergence properties of the mixed finite element method. It was found that 4 to 8 elements were sufficient for static analysis, while 16 were sufficient for stability analysis. In our study of the modes and frequencies of nonrotating beams we found that for three modes of any one type (bending or torsion, say) to be within 2% requires 32 elements.

Concerning stiffness and the design process, analysts would generally prefer to work on raw material and geometric properties whenever possible. For instance, summing ply thicknesses and presuming that each ply retains its nominal engineering properties makes life simple. We note that this simplicity might produce unrealistic results. Indeed, a trend described by Minguet and Dugundji was confirmed and studied further in our work – namely, laminate thickness measurements taken in two different stages of the curing process produce different stiffnesses, and physical reasoning leads to a still different thickness and corresponding stiffnesses. The last thickness is the hardest to obtain in the design process, but it leads to the most accurate stiffnesses.

There is very little in the literature that can aid in validation of predictive methods for natural frequencies of vibration for anisotropic beams of solid cross section. One study, Abarcar and Cunniff (1972), does contain experimental results with which results from the present work were compared. Our purely theoretical results for the free-vibration characteristics agreed with experimental data very well – better, in fact, than some of the theoretical results published by the experimenters based on identification of the beam properties from experiment!

Results from STAB also agree very closely with the U.S. Army code PFLT for aeroelastic stability of isotropic blades in hover. We believe that STAB does a better job of calculating the larger deflections than does PFLT. Indeed, some deficiencies in the PFLT results turned out to be due to its reliance on an ordering scheme. Because STAB does not use an ordering scheme, it does not exhibit these problems.

For composite blades, STAB's correlation with Yuan et al. (1992) is quite good, but its correlation with Hong and Chopra (1984, 1985) is quite poor except at zero ply-angle. Differences seem to be both quantitative and qualitative. The qualitative differences are especially apparent since their cases II and IV are said to exhibit a flap divergence for $C_T/\sigma = 0.10$ in Hong and Chopra (1984, 1985). This divergence, however, did *not* appear when generating the current results. In these cases their trim algorithm diverged, which may have been due to a combination of modeling errors in the work of Hong and Chopra plus their reliance on an ordering scheme. Also, we note that the excellent agreement between the analysis of Yuan et al. (1992) and ours, along with the observation of Fulton (1992) that the large variations in the damping due to modifications only affecting a small fraction of the cross section, are strong indications that the present model is more likely to be correct on this point.

All essential nonclassical effects were included in our model; indeed, the 3-D representation from which the model is derived accounts for all possible deformation of the blades and all possible elastic couplings. The approximations are in the development of the 1-D constitutive model, which cannot retain all of the 3-D information exactly. The nature of the asymptotical approximation is that certain short wave-length phenomena, such as the restrained warping effect, are not represented.

Modeling and Analysis Development

A common design for rotor blade sections is to utilize thin-walled construction. This is both weight-efficient and in accordance with the frequently-used approaches to manufacture with composite materials. The code TAIL developed by Robert Hodges and Mark Nixon, based upon the early work of Rehfield (1985), applies to thin-walled single cell blade box configurations. The thin-walled section, besides its practical usefulness, is a case where closed-form integral expressions for section stiffness are available. From a design and manufacturing point of view, the single-cell configuration is likely to be preferred for creating aeroelastically tailored configurations with elastic coupling incorporated, perhaps by layup over a honey comb shaped core that serves as a male tool for ease of manufacture. Consequently, special efforts have been made to improve the modeling of these configurations.

Nearly all modeling accomplished to date has been based upon displacement formulations and potential energy considerations. It is well known that such approaches yield analysis results that *overestimate stiffness*. This is unconservative in stability studies. Consequently, Dr. Rehfield developed a new modeling approach base upon complimentary energy considerations which tends to *underestimate stiffness*. This new theoretical approach yielded two benefits. The first is that compliances or flexibilities (the inverse of stiffnesses) are determined directly in terms of closed-form integrals. Secondly, the out-of-plane warping displacement can be estimated from closed-form expressions in a manner consistent with the thin-walled approximation. This formulation was presented to ARO in an informal report (Rehfield 1991a).

The original work which uncovered a new range of elastic coupling types (Rehfield 1985) was a linear, small-deflection theory. This has been extended to the geometrically nonlinear range of moderate rotations. While not as general as Dr. Hodges' formulations, this approximation yields an extremely useful means of evaluating the geometric stiffness effects of centrifugal blade axial loads on torsional stiffness and yields consistent static stability equations (Rehfield 1991b). Some static stability (i.e., buckling) results will be presented in a forthcoming invited paper (Rehfield 1993).

With the out-of-plane warping displacement known from complimentary energy-based theory above, it may be used to create a theory for beams with initial twist which is, relatively speaking, simple and easy to use. It was presented also to ARO in an informal report (Rehfield 1991c).

Limitations of time, resources and Dr. Rehfield's major health problems prevented the integration of these works (Rehfield 1991a, 1991b, 1991c) into design studies. Furthermore, considerable time and effort must be devoted to create sufficient understanding to permit rational design in the presence of both elastic coupling and pretwist.

Together with the above modeling issues which are "analysis" oriented, a preliminary design model for cross sections has been developed which aids in defining coupled configurations in the design process. We call it the "Ideal Tailored Box Model." This is a model specifically designed to be used in elastic tailoring studies of rotor blades and high aspect ratio wings. It is very simple and serves as a closed-cell counterpart to the "Ideal I-Beam Model" for bending about a single axis. It should prove very useful for (1) teaching, (2) optimization and parametric studies, (3) facilitating physical understanding, (4) providing Qualitative trend information and (5) isolating independent designer-controlled mechanisms. It's development was jointly supported by NASA, and it is fully described in (Rehfield, Chang and Zischka 1992). Also given is an application to a rotor blade configuration supplied to us by Mark Nixon. This section model has the added advantage that all stiffness and compliances are found from simple, closed-form expressions.

Design Information

A survey of companies, which included Bell, Boeing, McDonnell Douglas and Sikorsky, was performed to learn about blade structural design approaches used in industry. What has emerged is a picture of individual company approaches which depend upon company historical data from previous designs, proprietary practices, iteration, and static and fatigue coupon testing. It has not been possible to unify the different approaches. This is made difficult, in part, by the ways that the individual companies organize their work units and by their use of company proprietary software that is often poorly documented and has undergone evolutionary modifications over time.

Reliance upon historical data and flight test data for design insures that innovation will likely be slow slow in coming. Parameter ranges that depart far from previous experience will be resisted. In particular, balanced layups which exhibit no elastic coupling are used to reduce or eliminate manufacturing-related warping of parts.

We believe that unbalanced layups are the most efficient for producing elastic coupling. Relatively little is known about failures or damage processes in such configurations. Some preliminary tests run at Northrop[2] suggest that a "scissor-type" damage mode can occur. In the absence of more information and data, we have dealt with configurations which are similar to those treated previously in the literature. This has the additional benefit of validating the analytical results.

Design Studies

Two soft in-plane rotor configurations, R1 and R2, were used for aeroelastic stability design studies. Rotor R2 was an extension-twist coupled rotor based upon the rotor of Hodges et al. (1987). Rotor R1, however, had two laminate designs, $L2_e$ ($[0°_2/\zeta_4]$) and $L3_e$ ($[\zeta,\zeta-90°,\zeta,(\zeta-90°)_2,\zeta]$), both of which were extension-twist designs.

Although the laminate for rotor R2 was fixed, the laminates for rotor R1 had a variable ply angle. The R1 laminate designs, along with their accompanying box beam dimensions (which were constrained to fit within the selected airfoil), were chosen because they gave realistic nondimensional rotating frequencies which did not significantly vary as the ply angle was swept from zero to ninty degrees. In addition, the two laminate designs were considered to fairly represent the entire class of extension-twist designs.

For rotor R2, a sweep of the thrust level was used to investigate the lead-lag damping variation with hovering flight condition. Results were calculated for various stiffness models. It was demonstrated that a significant error appeared for this case (especially at high thrust levels) when bending-shear coupling was neglected.

For rotor R1, sweeps of thrust level were made for each laminate design for various values of the ply angle. These studies demonstrated, as suggested by Hong and Chopra (1984, 1985), that the elastic coupling available from laminate design was able to noticeably affect the lead-lag damping level for most thrust levels. In general, however, these laminate designs were not very sensitive to either the direct shear effects or the nonclassical (parasitic) coupling of bending-shear.

In general, the accuracy of the composite predictions was found to depend on the quality of the cross-sectional stiffnesses. The two-dimensional analyses used, however, gave nearly identical results for many cases because of their high quality. The performance of the "classical" stiffnesses (which ignore shear deformation effects), however, was poor for several cases.

Recommendations

In spite of the generality of the work done under this grant, there are certainly areas which deserve additional work. Indeed, it should be emphasized that far more design studies should be done than those we were able to complete once our model was validated. Even so, the model itself could be made more applicable to realistic helicopter design by including "better" aerodynamics, such as the Peters-He model and forward flight effects, and by also modeling the flexbeam or yoke (a more complete rotor system model). We also strongly favor the creation of additional experimental data sets for validation and correlation of composite blade analyses.

---

[2] Deo, R., private communication to Dr. Rehfield, Northrop Corporation, Hawthorne, California, 1991.

It is clear that we need to emphasize "synthesis" now that many "analysis" issues are resolved by this work and others. Additional understanding of elastic couplings on dynamics is still needed as are guidelines for design of elastically coupled rotors.

Contributions

Thesis

Mark V. Fulton: "Stability of Elastically Tailored Rotor Blades." Ph.D. Dissertation, School of Aerospace Engineering, Georgia Institute of Technology, June 1992.

Journal Papers

Rehfield, Lawrence W.; and Atilgan, Ali R.: Understanding New Tailoring Mechanisms for Thin-Walled Composite Beams. *J. Composites Technology and Research*, submitted for publication, 1990.

Atilgan, Ali R.; and Rehfield, Lawrence W.: Vibrations of Composite Thin-Walled Beams with Designed-in Elastic Couplings. *J. Composites Technology and Research*, submitted for publication, 1990.

Hodges, Dewey H.; Atilgan, Ali R.; Fulton, Mark V.; and Rehfield, Lawrence W.: Free-Vibration Analysis of Composite Beams. *J. American Helicopter Society*, vol. 36, no. 3, July 1991, pp. 36 – 47.

Atilgan, Ali R.; Hodges, Dewey H.; and Fulton, Mark V.: Nonlinear Deformation of Composite Beams: Unification of Cross-Sectional and Elastica Analyses. *Applied Mechanics Reviews*, vol. 44, no. 11, Part 2, Nov. 1991, pp. S9 – S15.

Atilgan, Ali R.; and Hodges, Dewey H.: Unified Nonlinear Analysis for Nonhomogeneous Anisotropic Beams with Closed Cross Sections. *AIAA Journal*, vol. 29, no. 11, 1991, pp. 1990 – 1999.

Hodges, Dewey H.; Atilgan, Ali R.; Cesnik, Carlos E. S.; and Fulton, Mark V.: On a Simplified Strain Energy Function for Geometrically Nonlinear Behavior of Anisotropic Beams. *Composites Engineering*, vol. 2, nos. 5 – 7, 1992, pp. 513 – 526.

Meeting Papers

Hodges, Dewey H.; Atilgan, Ali R.; Fulton, Mark V.; and Rehfield, Lawrence W.: Dynamic Characteristics of Composite Beam Structures. *Proceedings of the American Helicopter Society National Specialists' Meeting on Rotorcraft Dynamics*, Arlington, Texas, Nov. 13 – 14, 1989.

Rehfield, L. W.; Chang, Y. S.; and Atilgan, A. R.: New, Unusual and Nonclassical Behavior of Thin-Walled Composite Structures. *Proceedings of the Eighth International Conference on Composite Materials*, Honolulu, Hawaii, July 15 – 19, 1991.

Meeting Papers (continued)

Hodges, Dewey H.; and Atilgan, Ali R.: Asymptotical Modeling of Initially Curved and Twisted Composite Rotor Blades, Paper no. 47, *Proceedings of the American Helicopter Society International Technical Specialists' Meeting on Rotorcraft Basic Research*, Atlanta, Georgia, March 25 – 27, 1991.

Atilgan, Ali R.; Hodges, Dewey H.; Fulton, Mark V.; and Cesnik, Carlos E. S.: Application of the Variational-Asymptotical Method to Static and Dynamic Behavior of Elastic Beams. AIAA Paper 91-1026, *Proceedings of the 32nd Structures, Structural Dynamics, and Materials Conference*, Baltimore, Maryland, April 8 – 10, 1991, pp. 1078 – 1093.

Hodges, Dewey H.; Atilgan, Ali R.; Cesnik, Carlos E. S.; and Fulton, Mark V.: On a Simplified Strain Energy Function for Geometrically Nonlinear Behavior of Anisotropic Beams. *Proceedings of the 17th European Rotorcraft Forum*, Berlin, Germany, Sept. 24 – 27, 1991, Paper no. 91-80, pp. 617 – 628.

Fulton, Mark V.; and Hodges, Dewey H.: "Stability Analysis for Elastically Tailored Rotor Blades." *Developments in Theoretical and Applied Mechanics*, vol. 16, (Proceedings of the Sixteenth Southeastern Conference on Theoretical and Applied Mechanics, Nashville, Tennessee, April 12 – 14), 1992, pp. II.3.12 – II.3.18.

Fulton, Mark V.; and Hodges, Dewey H.: "Application of Composite Rotor Blade Stability Analysis to Extension-Twist Coupled Blades." AIAA Paper 92-2254. *Proceedings of the 33rd Structures, Structural Dynamics, and Materials Conference*, Dallas, Texas, April 13 – 15, 1992, pp. 1989 – 1995.

Fulton, Mark V.; and Hodges, Dewey H.: "Aeroelastic Stability of Hingeless Elastically Tailored Blades in Hover." *Proceedings of the ASME Winter Annual Meeting*, Anaheim, California, Nov. 8 – 13, 1992.

Rehfield, L. W.: "A First-Order Nonlinear Theory for Thin-Walled Composite Beams With Closed Cross Sections," Invited paper to be presented at the 9th International Conference on Composite Materials, Madrid, Spain, July 12 – 16, 1993.

Reports

[3] Rehfield, L. W., "A New Complimentary Energy Based Theory for This-Walled, Closed-Cell Composite Beams," Report to Army Research office, August 1991(a).

[3] Rehfield, L. W., "A First Order Nonlinear Theory for Thin-Walled Composite beams With Closed Cross Sections," Report to Army research Office, June 1991(c).

[3] Rehfield, L. W., Chang, S. and Zischka, P. J., "Modeling and Analysis Methodology for Aeroelastically Tailored Chordwise Deformable Wings," NASA Contractor Report 189620, July 1992.

---

[3] Not formally published due to Dr. Rehfield's health problems.

Presentations

Atilgan, Ali R.; and Rehfield, L. W.: Vibrations of Composite Thin-Walled Beams with Designed-in Elastic Couplings. Presented at the Fifth Japan-U.S. Conference on Composite Materials, Parthenon Tama, Tama-City, West of Tokyo, Japan, June 24 – 27, 1990.

Hodges, Dewey H.; Atilgan, Ali R.; Cesnik, Carlos E. S.; and Fulton, Mark V.: On a Simplified Strain Energy Function for Geometrically Nonlinear Behavior of Anisotropic Beams. Presented at the Army Research Office Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, University of Maryland, College Park, Maryland, Nov. 19 – 21, 1991.

Fulton, Mark V.: Stability of Elastically Tailored Rotor Systems. Presented at the Army Research Office Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, University of Maryland, College Park, Maryland, Nov. 19 – 21, 1991.