NASA-CR-191803

p. 7

Final Technical Report

Aeroelastic Stability and Response of Rotating Structures

NASA Grant NSG-3139

Theo G. Keith, Jr.
Department of Mechanical Engineering
University of Toledo

(NASA-CR-191803) AEROELASTIC STABILITY AND RESPONSE OF ROTATING STRUCTURES Final Technical Report (Toledo Univ.) 7 p

N93-16560

Unclas

G3/08 0140846

January 1993

Aeroelastic Stability and Response of Rotating Structures

Summary of Grant NSG-3139

A summary of the work performed under NASA grant number NSG-3139 is presented herein. More details of these efforts can be found in the cited references. This grant has led to the development of analysis methods for predicting loads and instabilities of wind turbines, and the initiation and development of three new areas of research to aid the Advanced Turboprop Project (ATP).

(A) Analysis of Wind Turbines

This work was started to assist the Department of Energy (DOE) to analyze and design efficient wind turbines for extracting wind energy. Initially, two versions of a commercially developed computer program (MOSTAS) for predicting loads and instability of wind turbines, were evaluated by comparing with measured data for two bladed machines. It was concluded that the version having the periodic coefficients solution performed better than the version that used time averaging, Refs. A.1 and A.2. At the same time, a simple model with five degrees of freedom, was developed for investigating the whirl flutter stability of horizontal-axis wind turbines with a two-bladed teetering rotor. This model accounted for the out of plane bending motion of each blade, the teetering motion of the rotor, and both the pitching and yawing motions of the rotor support. The results showed that the DOE/NASA Mod-2 design was free from whirl flutter, Ref. A.3. A parametric study was performed showing the effect of variations in rotor support damping, rotor support stiffness, and the effect of pitch-flap coupling on pitching, yawing, teetering, and blade bending motions.

During this grant period, second degree non-linear governing equations for the analysis of vertical axis and horizontal axis wind turbines were developed, Refs. A.4 and A.5. These equations were then used to investigate the aeroelastic stability of many practical wind turbines. These equations are nonlinear because of large deformations of the flexible blades. A mathematical ordering scheme, which is consistent with the assumption of a slender beam, was used to discard some higher order elastic and inertial terms in the second-degree nonlinear equations. The blade aerodynamic loading accounted for both wind shear and tower shadow; it was obtained from strip theory based on a quasi-steady approximation of two-dimensional, incompressible, unsteady, airfoil theory. The resulting equations had periodic coefficients.

The influence of second degree and third degree geometric nonlinear terms on the vibration and stability characteristics of rotating, pre-twisted, and pre-coned blades, was studied in Refs. A.6 and A.7. The equations were solved using the Galerkin method. The predictions were compared with those obtained from MSC / NASTRAN and also with measured data. It was shown that the spurious instabilities, observed for thin, rotating blades when second degree geometric nonlinearities were used, could be eliminated by including the third degree elastic nonlinear terms. The inclusion of third degree terms improved the correlation between theory and experiment. A study to investigate the vibration and buckling of rotating, pre-twisted, pre-coned beams including Coriolis effects was performed in Refs. A.8-A.10. It was shown that the Coriolis effects were necessary for blades of moderate-to-large thickness ratios. Thus, the linear Coriolis terms associated with pre-cone could be neglected in the dynamic analysis of advanced turboprop (propfan) blades. The results also showed the possibility of buckling due to centrifugal softening terms for large values of pre-cone and rotation. During this study, an improved finite difference method was also developed; this improvement eliminated most of the shortcomings associated with conventional first order methods and also provided faster convergence, Refs. A.11-A.13.

(B) Aeroelastic Analysis methods for cascades including blade and disk flexibility

The first new area of research aimed at helping the Advanced Turboprop Project is cascade aeroelasticity i.e., an investigation of the response and stability of multibladed structures, such as propfans, turbines, and compressors. This is an important topic in the design of propulsive elements of any engine. The work started with the pioneering paper on the development of methods for the stability analysis of mistuned rotors, Ref. B.1. This paper used only a typical section structural model, with bending and torsion motion, in incompressible flow. However, this formed the basis for all the methods developed to date. The aerodynamic models were later improved to include the effects of compressible flow in general and supersonic flow, in particular, Refs. B.2 and B.3. Even this simple model produced considerable insight into stability and response aspects of cascades. The study showed that mistuning is beneficial for the stability of the cascade, but not for its response. Since mistuning exists naturally, this has to be studied very carefully. The study resulted in the development of computer programs TUNEBT and MISER, which are widely used even today in the design and testing of the stability and forced response of cascades.

The later studies concentrated mainly on the development of the structural model. The typical section structural model was replaced by a beam model, Refs. B.4-B.8, and a finite element model, Ref. B.9. The available two-dimensional theories were used in a stripwise manner. The structural model was extended to include disk flexibility, which required a special formulation to include the effect of both rotating and non-rotating parts, Ref. B.10. The corresponding computer programs, BEAM, ASTROP3, and BEDE are now routinely used for further research. During this period, methods to automate flutter calculations were also developed. These methods drastically reduced the time required to calculate the flutter conditions of a cascade, propfan or of a turbomachine, Ref. B.11. All the developments until 1988 were included in the survey paper presented at Lewis Structures Technology, Ref. B.12.

(C) Stall flutter analysis

The second area of research, which is of utmost importance for propellers and propfans, concerns stability in separated flow regions. Separation of the flow in a vibrating environment, increases loading levels up to three times the static loading, and results in fatigue failure of the blades. Three available semi-empirical models suitable for the calculation of the loading during stall were reviewed, Ref. C.1. It was concluded that the ONERA model which involves fewer parameters, and is easy to apply, was the most suitable candidate for development for application to propfans. A computer program was developed to implement these models; this program was utilized in propfan blade stall flutter analyses, Refs. C.2 and C.3. It was found that the models predicted the onset of stall, as observed in experiments. However, static stall data for NACA 16 series airfoils was required for good correlation. The associated computer program, ASTROP2-STALL was delivered to Hamilton Standard for evaluation and use. The publication Ref. C.3 was awarded the Structural Dynamics Branch best paper of the year for 1990

(D) Computational Aeroelasticity

The third area of research, which was started under this grant and led to leading-edge technology, is computational aeroelasticity. It was known that linear aerodynamic theories used in the cascade aeroelastic studies mentioned above, could not account for effects of airfoil shape, angle of attack, and transonic flow conditions. Only through computational methods, could these effects be accounted for properly. Initially, to become familiar with the broad area of computational aeroelasticity, a computer program was developed to study isolated airfoils. The objective of the study was to develop a Navier-Stokes / Euler solver and to couple it with a typical section structural model. It was also aimed at evaluating the applicability of the solver to very thin airfoils, such as those in propfans. The study, for attached flow conditions (no flow separation) demonstrated that the computer program was able to handle thin airfoils, Ref. D.1. This study was also directed to investigate the effects of rotational flow, viscosity, thickness, and shape on transonic flutter dip phenomena. The predicted flutter Mach number for a simulated SR5 propfan blade was about 4.5% less than that obtained in experiment.

To reduce the computational times and to obtain a basic understanding of analysis methods for cascades, a time accurate full potential solver was developed and used to investigate the stability of a nine bladed cascade. Again, a typical section structural model was used, Ref. D.2. To achieve good agreement with wind-tunnel experimental data, a time domain method was proposed and verified, Ref. D.3. Since time domain methods are time consuming, efficient methods were developed to reduce the computational time for calculating the unsteady aerodynamic coefficients, Ref. D.4. These methods, and a parametric study including mistuning, comparison of results from both frequency domain, and time domain methods, were presented in a Ph.D. thesis, Ref. D.5.

Bibliography

A.1. Kaza, K.R.V., Aeroelastic Stability of Wind Turbine Blades, Workshop on Wind Turbine Structural Dynamics, NASA CP 2034, November 15-17, 1977.

A.2. Kaza, K.R.V., Janetzke, D.C. and Sullivan, T.L. Evaluation of Mostas Computer Code for Predicting Dynamic Loads in Two-Bladed Wind Turbines, AIAA J., Vol. 4, 1980, pp. 162-169, also NASA TM 79101, 1979.

A.3. Janetzke, D.C. and Kaza, K.R.V. Whirl Flutter Analysis of a Horizontal-Axis Wind Turbine with a Two-Bladed Teetering Rotor, Solar Energy, Vol. 31, No. 2, pp. 173-182, 1983.

A.4. Kaza, K.R.V., Aeroelastic Equations of Motion of a Darrieus, Vertical-Axis Wind-Turbine Blade, NASA TM 79295, Dec. 1979.

A.5. Kaza, K.R.V., Nonlinear Aeroelastic Equations of Motion of Twisted, Nonuniform, Flexible Horizontal-Axis Wind Turbine Blades, NASA CR 159502, July 1980.

A.6. Kvaternik, R.G., White, Jr., and Kaza, K.R.V., Nonlinear Flap-Lag-Axial Equations of a Rotating Beam with Arbitrary Precone Angle, AIAA 78-491, 19th Structures, Structural Dynamics and Materials Conference, Bethesda, Maryland, April 3-5, 1978.

A.7. Subrahmanyam, K.B. and Kaza, K.R.V., Influence of Third-Degree Geometric Nonlinearities on the Vibration and Stability of Pretwisted, Preconed, Rotating Blades , NASA TM 87307, May, 1986.

A.8. Subrahmanyam, K.B. and Kaza, K.R.V., Nonlinear Flap-Lag-Extensional Vibrations of Rotating, Pretwisted, Preconed Beams Including Coriolis Effects, NASA TM 87102, 1985.

A.9. Subrahmanyam, K.B. and Kaza, K.R.V., Vibration and Buckling of Rotating, Pretwisted, Preconed Beams including Coriolis effects, J. Vibration, Acoustics, Stress, and Reliability in Design, Vol. 108, pp. 140-149, April 1986. also, NASA TM 87004, Sept. 1985.

A.10. Subrahmanyam, K.B., Kaza, K.R.V., Brown, G.V. and Lawrence, C., Nonlinear Bending-Torsional Vibration and Stability of Rotating, Pretwisted, Preconed Blades Including Coriolis Effects, NASA TM 87207, January, 1986.

A.11. Subrahmanyam, K.B. and Kaza, K.R.V., An Improved Finite-Difference Analysis of Uncoupled Vibrations of Tapered Cantilever Beams, NASA TM 83495, Sept. 1983.

A.12. Subrahmanyam, K.B. and Kaza, K.R.V., Finite Difference Analysis of Torsional Vibrations of Pretwisted, Rotating, cantilever Beams with Effects of Warping, J. Sound and Vibration, Vol. 99, 213-224, 1985.

A.13. Subrahmanyam, K.B. and Kaza, K.R.V., Vibration Analysis of Rotating Turbomachinery Blades by an Improved finite difference method, Int. J. Numer. Methods in Engg., Vol. 21, pp. 1871-1886, 1985, correction in Vol. 23, 1986.

B.1. Kaza, K.R.V. and Kielb, R.E., Flutter and Response of a Mistuned Cascade in Incompressible Flow, AIAA J., vol. 20, No. 8, Aug. 1982, pp. 1120-1127, also NASA TM 81674, April 1981.

B.2. Kielb, R.E. and Kaza, K.R.V., Effects of Structural Coupling on Mistuned Cascade Flutter and Response, J. Engg. for Gas Turbines and Power, vol. 106, pp. 17-24, January 1984, also NASA TM 83049, 1983.

B.3. Buseby, B.C., Kaza, K.R.V. and Keith, T., The effects of strong shock loading on coupled bending-torsion flutter of tuned and mistuned cascades, presented at the 10th Biennial ASME Design Engineering Conference and Exhibit on Mechanical Vibration and Noise, Cincinnati, OH, Sept. 10-13.

B.4. Kaza, K.R.V. and Kielb, R.E., Coupled Bending-Bending-Torsion Flutter of a Mistuned Cascade with Nonuniform Blades, Presented at the 23rd Structures, Structural Dynamics and Materials Conference, New Orleans, Louisiana, May 10-12, 1982. also NASA TM 82813,1982.

B.5. Kaza, K.R.V. and Kielb, R.E., Flutter of Turbofan Rotors with Mistuned Blades, AIAA J., vol. 22, No. 11, Nov. 1984, pp. 1618-1625.

B.6. Kielb, R.E. and Kaza, K.R.V., Aeroelastic Characteristics of Cascade of Mistuned Blades in Subsonic and Supersonic Flows, J. Vibration, Stress and Reliability in Design, vol. 105, pp. .1120-1127, 1983.

B.7. Kielb, R.E. and Kaza, K.R.V., Flutter of Swept Fan Blades, J. Engg. for Gas Turbines and Power, vol. 107, pp. 394-398, April 1985.

B.8. Mehmed, O. Kaza, K.R.V., Lubomski, J.F., Kielb, R.E., " Bending-Torsion Flutter of a Highly Swept Advanced Turboprop," NASA TM-82975, October, 1982.

B.9. Kaza, K.R.V., Mehmed, O., Narayanan, G.V. and Murthy, D.V., Analytical Flutter Investigation of a Composite Propfan Model, NASA TM 88944, April 1987.

B.10. Kaza, K.R.V. and Kielb, R.E., Vibration and Flutter of Mistuned Bladed-Disk Assemblies, J. Prop. and Power, vol. 1, No. 5, Sept-Oct, pp. 336-344, also NASA TM 83634, 1984.

B.11. Murthy, D.V. and Kaza, K.R.V., A Computational Procedure for Automated Flutter Analysis, NASA TM 100171, 1987.

B.12. Kaza, K.R.V., "Development of Aeroelastic Analysis Methods for Turborotors and Propfans - Including Mistuning", 1-247:1-262., Presented at the Lewis Structures Technology-1988, Vol.1, Structural Dynamics, NASA CP 3003.

C.1. Reddy, T.S.R. and Kaza, K.R.V., A Comparative Study of Some Dynamic Stall Models, NASA TM 88917, 1987.

C.2. Reddy, T.S.R. and Kaza, K.R.V., Stall Flutter Analysis of an Unswept Propfan Blade with Semi-empirical Dynamic Stall Models, NASA TM 4083, 1989.

C.3. Reddy, T.S.R. and Mehmed, O., Aeroelastic Analysis of Prop fan Blades with a Semiempirical Dynamic Stall Model, AIAA-89-2695, 25th Joint Propulsion Conference, Monterey, CA, July 10-12, 1989.

D.1. Reddy, T.S.R., Srivastava, R. and Kaza, K.R.V., The Effects of Rotational Flow, Viscosity, Thickness, and Shape on Transonic Flutter Dip Phenomena, AIAA Paper 88, 29th SDM Meeting.

D.2. Bakhle, M.A., Keith, T.G. Jr., and Kaza, K.R.V., App.lication of a Full Potential Solver to Bending-Torsion Flutter in Cascades, AIAA Paper 89-1386, April 1989.

D.3. Bakhle, M.A., Reddy, T.S.R. and Keith, T.G. Jr., Time Domain Flutter Analysis of Cascades Using a Full Potential Solver, AIAA Paper 90-0984, April 1990, also AIAA J. vol.30, no.1, 1992, pp163-170.

D.4. Bakhle, M.A., Mahajan, A.J., Keith, T.G. Jr. and Stefko, G.L., Cascade Flutter Analysis with Transient Response Aerodynamics, AIAA 91-0747, 29th Aerospace Sciences Meeting, Jan 7-10, 1991, Reno, Nevada., also NASA TM 103746, 1991.

D.5. Bakhle, M.A., Flutter Analysis of Cascades Based on the Two-Dimensional Full-Potential Equation, Ph.D. dissertation, College of Engineering, University of Toledo, Aug. 1991.