Aeroelastic Stability and Response of Rotating Structures

NASA Grant NSG-3139

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

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


