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Aeroelastic Analysis of Counter Rotation Fans

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Theo G. Keith, Jr.
Principal Investigator
Durbha V. Murthy
Co-Principal Investigator

Department of Mechanical, Industrial and Manufacturing Engineering
University of Toledo
Toledo, Ohio 43606

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AEROELASTIC ANALYSIS of COUNTER ROTATION FANS
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INTRODUCTION

Aeroelastic problems in turbomachinery and propfans can be static or dynamic in nature. The analysis of static aeroelastic problems is involved primarily with determination: (a) of the shape of the blades and the steady aerodynamic loads on the blades (which are inter-dependent), (b) of the resultant steady stresses and (c) of the static instability (divergence) margin, if applicable. In this project, we were concerned exclusively with dynamic aeroelastic behavior. The analysis of dynamic aeroelastic problems is involved with the determination: (a) of the unsteady aerodynamic loads on blades and the dynamic motion of the blades (which are again inter-dependent), (b) of the resultant dynamic stresses and their effect on fatigue life and (c) of the dynamic instability (flutter), if applicable.

There are two primary dynamic aeroelastic phenomena of interest to designers of turbomachinery and propfans: flutter and forced response. Flutter generally refers to the occurrence of rapidly growing self-excited oscillations leading to catastrophic failure of the blade. When certain nonlinear phenomena are present, flutter response may lead to a potentially dangerous limit cycle oscillation rather than an immediate catastrophic failure. Forced response generally refers to the steady-state oscillations that occur as a consequence of excitations external to the rotor in question. These excitations typically result from the presence of upstream obstructions, inflow distortions, downstream obstructions, or mechanical sources such as tip-casing contact or shaft and gear meshing. Significant forced response leads to blade fatigue, and at design conditions, generally contributes to a degradation of blade life. At other operating conditions, forced response may lead to catastrophic failure due to severe blade fatigue in a short duration of time.

The research activities of this project were aimed at development of analytical methods to better understand the above phenomena, development of computational models to accurately and efficiently predict them, development of schemes to validate these models using experimental and test data and development of marketing procedures for the dissemination of the developed methods and models to the industry. The focus for much of the work was the propfan and that for future work will be turbomachinery.

PROJECT PERSONNEL

Research under this grant has been primarily accomplished by Dr. Durbha V. Murthy, a Senior Research Associate in the Department of Mechanical Engineering at the University of Toledo and resident at the NASA Lewis Research Center. Dr.

Theo G. Keith, Jr., Distinguished University Professor in the Department of Mechanical Engineering at the University of Toledo is the Project Coordinator and has overall responsibility for the conduct of this work. Close collaborators include George Stefko, Oral Mehmed, David Janetzke, and Tony Kurkov of the Structural Dynamics Branch of NASA Lewis Research Center, Todd Smith and Mike Morel of Sverdrup Technology, Inc. (Lewis Research Center Group), Dr. Christophe Pierre of University of Michigan and Manohar Kamat and Brian Watson of Georgia Institute of Technology.

PROJECT OUTCOMES

The accomplishments under this grant are primarily in the areas of propfan flutter, new numerical techniques for flutter boundary prediction, the influence of mistuning on aeroelastic vibration behavior and parallel processing for aeroelastic analysis.

The work involving the analytical methods included the development of a modal method for the aeroelastic analysis of propfans (Kaza, Mehmed, Narayanan and Murthy, 1989) and the formulation of a complex transcendental eigenvalue problem with real pairs of eigenvalues for flutter analysis (Murthy and Kaza, 1989; Murthy, 1991). It was shown that the normal modes formulation can be successfully used to unite large and complicated structural and unsteady aerodynamic models to produce a small aeroelastic model. The aeroelastic model can then be used to solve the flutter, as well as the forced response, problems. Further, it was shown that finding the matched flutter point is equivalent to solving a complex transcendental eigenvalue problem with pairs of real eigenvalues. This interpretation leads to a direct solution procedure that avoids many of the difficulties, associated with tracking of eigenvalues, that hamper the reliability of automated flutter analysis programs.

A new quasi-Newton method was developed for the solution of the flutter eigenvalue problem (Murthy and Kaza, 1989; Murthy, 1991). This method possesses excellent convergence characteristics and is computationally more efficient than other methods. The computational strategy was to approximate the Jacobian matrix in terms of generalized aerodynamic force derivatives and to update the Jacobian matrix in successive iterations only in the direction of the last step keeping it constant in the direction orthogonal to the last step. Also, a semi-analytical technique for the sensitivity analysis of linear aerodynamic models (Murthy and Kaza, 1991), which could reduce the computational cost of aeroelastic analysis as well as design, and two analytical techniques for the sensitivity analysis of the flutter problem (Murthy, 1991), which could reduce the computational cost of aeroelastic design, were developed.

Further, the aeroelastic analysis was adapted for efficient execution on a multi-processor parallel computer systems. Initially, a commercial shared memory system, the Alliant FX/80, was used (Murthy and Janetzke, 1991a). This implementation achieved efficiencies up to 75 percent using 7 processors. Only moderate modification of the corresponding sequential code was performed by using a high-level approach, where parallel paths were identified in the computationally intensive portion of the sequential code and parallelized. The calculation of the unsteady aerodynamic coefficients was parallelized and the independent concurrent subtasks were scheduled to reduce processor idle time and improve speedup and efficiency. The results obtained demonstrated the potential for parallelization of aeroelastic analysis procedures, particularly those using panel methods for calculating unsteady aerodynamic forces. The speedup and efficiency gained in the aerodynamic coefficient computation would also contribute to the overall speedup and efficiency of an automated multi-disciplinary design procedure of which the aeroelastic analysis would form a part.

A more interesting effort towards the implementation of the aeroelastic analysis on parallel computers used a distributed memory computer system consisting of a network of transputer processors (Janetzke and Murthy, 1991). The transputer is a high performance Reduced Instruction Set Computer (RISC) and was made possible by advances in VLSI microcircuit technology that have allowed the placement of an entire computer with memory and communication channels on a single chip. One of the chief attractions of a transputer network system is its low cost relative to computers of comparable performance. For the unsteady aerodynamic portion of the aeroelastic analysis, efficiencies up to 86 percent using 32 processors are demonstrated, using dynamic scheduling of parallel subtasks. These and other ways of parallelizing aeroelastic calculations were reviewed during the period of this grant (Murthy and Janetzke, 1991b).

As part of an effort to develop computer programs for designers, all the above techniques were implemented in FORTRAN computer programs, mostly as extensions of the ASTROP aeroelastic analysis code developed at the NASA Lewis Research Center.

Potentially damaging dynamic behavior of mistuned systems has attracted great attention in the recent past, even though most of the work has neglected the effect of unsteady aerodynamic forces. Efforts under this grant have demonstrated some of the consequences of the presence of mistuning in single rotor systems, including the effect of unsteady aerodynamic forces. For example, Mehmed and Murthy (1991) demonstrated, using experimental data, that large and intuitively unpredictable variations can occur in the aeroelastic response of propfan blades to off-axis flow because of mistuning. It was recommended that mistuning be considered in designing propfans for aeroelastic forced response. Also, a recent study (Pierre and Murthy, 1991) demonstrated the drastic changes in aeroelastic characteristics of single rotor systems, such as the loss of aeroelastic eigenstructure and the localization of aeroelastic mode shapes. Localization of aeroelastic mode shapes may result in only a few blades absorbing all the energy of external excitation and suffering much more fatigue compared to the predictions by conventional methods that usually ignore mistuning. It was shown that these phenomena could occur for even small values of random mistuning, of the order that is normally present in realistic rotors. A perturbation method, that yielded insight into the qualitative behavior of mistuned aeroelastic systems, was developed. The perturbation method also provides a quick procedure to check if large changes can be expected by considering a given level of mistuning.

To demonstrate the mode localization phenomena in an existing engine structure, the High Pressure Oxygen Turbo Pump (HPOTP) of the Space Shuttle Main Engine (SSME), which had the structural and aerodynamic characteristics typical of the new generation high-energy turbines, was studied (Pierre, Smith and Murthy, 1991). The aeroelastic behavior of the HPOTP turbine blades was obtained using a finite element structural model and an advanced aerodynamic model that accounts for the effects of camber, incidence and thickness. The extreme sensitivity to mistuning and the occurrence of localized vibrations were demonstrated for this class of turbines. A second major contribution has been the preliminary investigation into a powerful sensitivity measure that could allow the global prediction of mistuning effects based solely on the knowledge of the tuned system behavior. This sensitivity measure could help avoid engines that are pathologically sensitive to mistuning and is particularly suited for the design environment.

PROJECT PUBLICATIONS

The following publications have resulted from the research performed under this grant:

Janetzke, D. C. and Murthy, D. V., 1991, "Parallel Computation of Aerodynamic Influence Coefficients for Aeroelastic Analysis on a Transputer Network", Journal of Computing Systems in Engineering (to appear).

Kaza, K. R. V., Mehmed, O., Narayanan, G. V. and Murthy, D. V., 1989, "Analytical Flutter Investigation of a Composite Propfan Model", Journal of Aircraft, Vol. 26, No. 8, pp. 772-780.

Mehmed, O. and Murthy, D. V., 1991, "Experimental Investigation of Propfan Aeroelastic Response in Off-Axis Flow with Mistuning", Journal of Propulsion and Power, Vol. 7, No. 1, pp. 90-98.

Murthy, D. V. and Janetzke, D. C., 1991a, "Concurrent Processing Adaptation of Aeroelastic Analysis of Propfans", Computers and Structures (to appear).

Murthy, D. V. and Janetzke, D. C., 1991b, "Parallel Processing for the Analysis of Linear Aeroelastic Systems", presented at the 1st U. S. National Congress on Computational Mechanics, Chicago.

Murthy, D. V., 1991, "Solution and Sensitivity Analysis of a Complex Transcendental Eigenproblem with Pairs of Real Eigenvalues", International Journal for Numerical Methods in Engineering (to appear).

Murthy, D. V. and Kaza, K. R. V., 1989, "A Computational Procedure for Automated Flutter Analysis", Communications in Applied Numerical Methods, Vol. 5, No. 1, pp. 29-37.

Murthy, D. V. and Kaza, K. R. V., 1991, "A Semi-analytical Technique for Sensitivity Analysis of Unsteady Aerodynamic Computations", Journal of Aircraft, Vol. 28, No. 8, pp. 481-488.

Pierre, C. and Murthy, D. V., 1991, "Aeroelastic Modal Characteristics of Mistuned Blade Assemblies: Mode Localization and Loss of Eigenstructure", presented at the AIAA/ASME/ASCE/AHS/ASC 32nd Structures, Structural Dynamics and Materials Conference, Baltimore, Maryland.

Pierre, C., Smith, T. E. and Murthy, D. V., 1991, "Localization of Aeroelastic Modes in Mistuned High Energy Turbines", presented at the AIAA/ASME/SAE 27th Joint Propulsion Conference and Exhibit, Sacramento.