NASA-CR-205484

A Final Report to

National Aeronautics and Space Administration
Lewis Research Center
Structural Dynamics Branch

EFFECTS OF MISTUNING ON THE FORCED RESPONSE OF TURBOMACHINERY ROTORS

Grant NAG3-1163

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December 29, 1994

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1 PROJECT SUMMARY

The basic purpose of this research has been to develop a fundamental understanding of the effects of blade-to-blade dissimilarities, or mistuning, on the dynamics of nearly cyclic bladed-disk assemblies. This topic is of importance as mistuning has been shown to increase the forced response amplitudes of some blades significantly, and even to lead to blade failure. Furthermore, the current trend toward high performance propulsion turbomachinery designed for finite service life demands an accurate prediction of system performance and dynamics at the design stage.

This objective has been achieved by carrying out the following tasks. *First*, the investigation of the free and forced responses of representative, yet sufficiently simple blade assembly models that capture all the important characteristics of typical turbomachinery rotors. *Second*, the development of computational methods that predict the effects of mistuning in a systematic and reliable way, along with the development of a systematic reduced-order modeling procedure for mistuned bladed disks. *Third*, the application of these findings and the tools developed to an industrial rotor, namely the first stage of turbine blades of the oxidizer turbopump in the space shuttle main rocket engine (SSME).

The research supported by NASA has led to the development of a coherent theory for mistuned blade assemblies. The further implementation of these computational tools into the forced response prediction system currently under development in the Structural Dynamics Branch—FREPS—would enable the designer and the analyst (1) to identify types of blade assemblies highly sensitive to mistuning in various frequency and other parameter ranges and (2), to characterize mistuning effects on their *forced response* by predicting *true* response amplitudes and fatigue life estimates.

2 RESULTS FROM NASA SUPPORT

The status of the research supported by NASA Lewis is summarized below. For more detail on these research accomplishments, the reader is referred to the publications listed in Section 3.

2.1 Project Personnel

Research at The University of Michigan has been carried out by the principal investigator and by three graduate student research assistants (Gisli Ottarsson, Matthew Castanier, and Marlin Kruse). Gisli Ottarsson's doctoral dissertation [1] has been largely written with the help of NASA Lewis support.

Research has also proceeded in very close collaboration with NASA personnel, namely Durbha Murthy, Todd Smith, and Oral Mehmed. This has resulted in publications co-authored by the principal investigator and NASA Lewis researchers. The collaboration has been extremely fruitful and enriching for both parties.

2.2 Summary of Results

Research has proceeded primarily along the following lines:

- The characterization of the effects of mistuning on the aeroelastic properties of blade assemblies, including the in-depth investigation of the resulting vibration localization phenomena.

- The development of stochastic sensitivity measures that enable one to predict the extent of mistuning effects without requiring extensive computations.

- The systematic investigation of the effects of mistuning on the free vibration properties of common lumped-parameter models of blade assemblies, including the characterization of the resulting vibration localization phenomena and the examination of the effects of remote blade coupling on the sensitivity to mistuning.

- The analysis of the effect of closely-spaced blade modes on the sensitivity of the free dynamics of mistuned assemblies.

- The formulation of an optimization constraint to be used in the design for low sensitivity to mistuning.

- The formulation, from full finite element models, of a general reduced-order bladed disk model by a modified component mode analysis technique (this part of the research has been joint with the GUIde Consortium).

Research has also been initiated on the development of methods for calculating the statistics of forced response amplitudes of mistuned blade assemblies. Note that the efficient prediction of mistuned forced response, along with the integration of the associated computational techniques into the forced response prediction system (FREPS), has been one key objective of this research program—one that has not been totally fulfilled due to the unavailability of continuing funding.

The work that has been performed is described below.

Aeroelastic Mode Localization in Mistuned Assemblies

The effects of mistuning on the aeroelastic modal characteristics of blade assemblies have been examined, and the aeroelastic response has been shown to be *highly sensitive* to small mistuning. In particular, the aeroelastic modes of the system lose their constant interblade phase angle characteristic when mistuning is introduced: they become severely *localized* to a few blades and no pattern can discerned for the interblade phase angle. Furthermore, the root locus of the aeroelastic eigenvalues loses the regular pattern that characterizes the tuned system to become apparently randomly scattered for small mistuning. Deterministic perturbation schemes have been developed that explain and predict this sensitivity to mistuning. These sensitivity predictors rely solely on tuned system information and hence do not require extensive computations. The original contributions of the study lie in the evidence of these new phenomena and in the generality of the mistuning trends and phenomena uncovered: results are qualitatively valid for most typical blade assemblies. The results of the this study are reported in reference [2].

Aeroelastic Characteristics of Mistuned High-Energy Turbines

The general findings of reference [2] have been applied to the model of an actual mistuned high-energy turbine, namely the first stage of turbine blades of the oxidizer turbopump in the SSME. Results show an *extreme* sensitivity to mistuning for the aeroelastic modes of the turbine. The transition from constant-interblade-phase-angle modes to localized modes is very rapid and exhibits a complex behavior of the eigensolution. Severe localization occurs for blade frequency mistuning of approximately 0.1%—a mistuning level clearly unavoidable for a real turbine. The results obtained, reported in reference [3], provide a plausible explanation for the short fatigue life that have plagued the SSME turbopump turbines. Contrary to previously suggested failure mechanisms (*e.g.*, thermal shock), the work in reference [3] proposes a theory which is based on the intrinsic dynamic characteristics of mistuned rotors.

Sensitivity Measures for Mistuned Blade Assemblies

Two measures of sensitivity to mistuning have been developed, both of which are based on the free dynamics of the tuned assembly. The *first* measure is defined as the statistical average of the second-order perturbation of the free vibration aeroelastic eigenvalues due to random mistuning. The *second* measure is based on a wave transfer matrix formulation of the bladed disk. It is defined as the coefficient of the first-order mistuning term in the Taylor series expansion of the random wave transfer matrix in the small mistuning parameters. Both measures allow one to assess the significance of the effects of small mistuning, based solely upon tuned system information and an estimate of mistuning strength. They are inexpensive to calculate and therefore hold promise for being useful at the design stage. In particular, the need for high-cost mistuned free and forced response analyses is alleviated if a particular rotor design is found to be insensitive to random blade mistuning. The above two sensitivity measures are described and applied to various systems in references [4] and [5], respectively.

Characterization of Vibration Localization in Mono- and Bi-coupled Blade Assemblies

A wave transfer matrix methodology has been developed, that allows one to cast the dynamics of blade assemblies in terms of the coupling coordinates between the blades. A key advantage of this approach is that the size of the system is reduced to twice the number of coupling coordinates between blades, regardless of the number of blades, the complexity of blade geometry, and the number of blade modes considered. Another advantage of this strategy is that the dynamics of tuned and mistuned assemblies are simply obtained by multiplying the transfer matrices along the assembly.

The wave transfer matrix method has been first applied to assemblies which feature relatively simple coupling mechanisms between blades, namely mono-coupling (*i.e.*, a single generalized coupling coordinate) between adjacent blade/disk sectors. Using this approach, an interblade coupling factor has been defined for the mono-coupled blade assembly model, which provides a measure of the sensitivity of the system's free dynamics to mistuning in terms of all system parameters, including the frequency. A subsequent development has led to the formulation of a powerful descriptor of the degree of vibration localization due to mistuning: the *localization factor,* defined as the average rate of spatial exponential decay of the vibration amplitude along the assembly. Using the transfer matrix formulation, analytical approximations of the localization factor have been obtained, which characterize and quantify the effects of random mistuning on the free vibration modes in a stochastic, compact, and inexpensive way. The study of localization in mistuned mono-coupled assemblies is described in Reference [5].

The wave transfer matrix method has then been generalized to the case when coupling is not restricted to adjacent blade/disk sectors. The blade assembly model considered features a single disk-degree of freedom (DOF) per sector, an (possibly) arbitrary number of DOF's for each blade, and structural coupling among adjacent *as well as next-to-adjacent* disk-DOF's. This system thus features two coupling coordinates and requires a four by four transfer matrix for the modeling of a blade/disk sector. The effect of non-adjacent sector coupling on the sensitivity to mistuning has been examined and an analytical criterion derived, which dictates the conditions under which it is legitimate to neglect the coupling among non-adjacent sectors and retain only that among adjacent ones. This tells one when the simplifying assumption of accounting only for nearest-neighbor interactions among blades is valid, that is, does not result in dynamics which are qualitatively different from those of the actual assembly (recall that real rotors feature some degree of coupling among all blades through the disk). These results are described in reference [6].

Dynamics of Mistuned Assemblies with Closely-Spaced Blade Modes

The primary objective of this research, carried out in collaboration with Dr. Durbha Murthy of NASA Lewis, has been to examine mistuning effects and vibration localization phenomena in assemblies which feature two blade modes with *close* natural frequencies; for example, a bending mode and a torsion mode, or two modes of a plate-like blade such as tip modes. The interaction of two close blade modes has been analyzed for a simple model with aerodynamic interblade coupling, and the resulting effect on the sensitivity of the assembly dynamics to mistuning has been assessed in terms of blade mode frequency separation. A paper that describes these results has been written up [7].

Formulation of an Optimization Constraint for Low Sensitivity to Mistuning

A constraint has been formulated which could allow the designer to account for mistuning effects in the optimal design of engine rotors, such that their forced response is not adversely affected by mistuning in a significant way. This has been carried out by taking advantage of the inexpensive tools which had been previously developed for the prediction of mistuning effects, namely the sensitivity index introduced in Reference [5]. The concept of *designing for low sensitivity to mistuning* is a novel one and represents a significant leap from classical mistuning analyses of blade assemblies. It holds promise as a future research topic. The development of the optimization constraint for mistuning, along with an illustrative example for a simple blade assembly model, has been written up in reference [8].

Reduced-Order Modeling Formulation for Mistuned Bladed Disks

This part of the research, supported jointly by the GUIde Consortium on Forced Response, has centered on the generation of accurate reduced-order models of bladed disks from detailed finite element models. Key desirable features of these simpler models are (1) the model parameters ought to be systematically obtainable from the finite element analysis of a single blade/disk sector, (2) the interblade coupling mechanisms ought to be captured accurately, implying precise disk and disk/blade interface modeling and systematic inclusion of motion-dependent aerodynamic effects and (3), the blade frequency mistunings ought to be independent inputs to the model, which essentially rules out a modal analysis of an entire disk/blade sector (in which the blade frequencies are embedded) as a viable reduction procedure. In order to achieve these features, various modeling strategies were reviewed and assessed. Although lumped-parameter models were found to capture adequately the dynamics of most assemblies in a given desired frequency range, one major problem associated with them is the lack of a systematic procedure for the identification of the model parameters from finite element data. The modeling methodology which was selected is based upon a component mode analysis of the bladed disk, whereby one substructure consists of the disk and the other substructures of the blades. The disk motion is represented by families of nodal diameter natural modes, each family corresponding to a number of nodal circles. The blade motion is written as a superposition of "static" modes, which are induced by the disk elastic deformation at the blade root, and elastic motion, which is expanded as a series in the natural modes of vibration of the blade with a fixed base. Because of the use of the "static" blade modes, which arise due to the blade root deformation caused by the disk, the assembly of the disk and blade substructures is automatic. After derivation of the equations of motion, the total number of degrees of freedom for the (mistuned) assembly is $N(M+N_b)$, where N is the number of sectors, M the number of nodal circle disk modes and N_b the number of elastic blade modes.

This reduced-order modeling strategy has been applied to three bladed-disk models with various levels of complexity: (1) continuous plate and beam models of the disk and the blades, respectively; (2) a simple finite element model (using eight-noded solid bricks) of a fictitious bladed-disk structure; (3) a complete finite element model of an actual blisk, provided by Textron-Lycoming. In these three cases, discretized equations of motion were derived and the frequency spectra of the "exact" model and the reduced-order models were compared. Very good agreement was achieved in all cases over a wide frequency range, thereby establishing the validity of the reduced-order modeling formulation for tuned systems. A comparison of natural frequencies and mode shapes of mistuned full and reduced-order models indicated the appropriateness of the procedure for the study of mistuning effects. Finally, it was shown that in all cases the coupling between two blades decreases rapidly as the number of blades located between them increases, therefore suggesting that simplified coupling models can be generated systematically with this approach. This would allow for the use of the wave transfer matrix method, which is well suited for an effective prediction of mistuning effects.

A paper has been written that describes the reduced-order modeling formulation and some of the results obtained to date. It is listed below as reference [9].

3. List of Publications from NASA Support

1. Ottarsson, G., "Dynamic Modeling and Vibration Analysis of Mistuned Bladed Disks," *Ph.D. Dissertation*, The University of Michigan, 1994.

2. Pierre, C., and Murthy, D. V., "Aeroelastic Modal Characteristics of Mistuned Blade Assemblies: Mode Localization and Loss of Eigenstructure," AIAA paper 91-

1218, 32nd AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference, April 8-10, 1991, Baltimore, Maryland. Also, NASA Technical Memorandum 104519. Also, *AIAA Journal*, Vol. 30, No. 10, October 1992, pp. 2483-2496.

3. Pierre, C., Smith, T. E., and Murthy, D. V., "Localization of Aeroelastic Modes in Mistuned High-Energy Turbines," AIAA paper 91-3379, 27th AIAA/ASME Joint propulsion Conference, June 24-27, 1991, Sacramento, California. Also, NASA Technical Memorandum 104445. Also, *Journal of Propulsion and Power,* Vol. 10, No. 3, May-June 1994, pp 318-328.

4. Murthy, D. V., and Pierre, C., "Stochastic Sensitivity Measure for Mistuned High-Performance Turbines," Fourth International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (*ISROMAC-4*), Honolulu, Hawaii, April 5-9, 1992. Also, NASA Technical Memorandum 105821. Also, submitted to the *ASME Journal of Engineering for Gas Turbines and Power.*

5. Ottarsson, G., and Pierre, C., "A Transfer Matrix Approach to Vibration Localization in Mistuned Blade Assemblies." Proceedings of the ASME Gas Turbine Conference, Cincinnati, Ohio, May 1993, ASME Paper 93-GT-115. Also, NASA Technical Memorandum 106112. Also, *Journal of Sound and Vibration*, 1994, in print.

6. Ottarsson, G., and Pierre, C., "Vibration Localization in Mono- and Bi-Coupled Mistuned Bladed Disks—A Transfer Matrix Approach," AIAA Paper 93-1492, 34th AIAA/ASME Structures, Structural Dynamics and Materials Conference, LaJolla, California, April 1993.

7. Pierre, C., and Murthy, D. V., "Aeroelastic Dynamics of Mistuned Blade Assemblies with Closely-Spaced Blade Modes," AIAA Paper 93-1628, 34th AIAA/ASME Structures, Structural Dynamics, and Materials Conference, LaJolla, California, April 1993.

8. Murthy, D. V., and Pierre, C., "An Efficient Constraint to Account for Mistuning Effects in the Optimal Design of Engine Rotors," Proceedings of the Fourth AIAA/USAF/NASA/OAI Symposium on Multidisciplinary Analysis and Optimization, Cleveland, Ohio, September 21-23, 1992. Also, accepted for publication in the *AIAA Journal* as a Technical Note, 1994.

9. Ottarsson, G., Castanier, M. P., and Pierre, C., "A Reduced-Order Modeling Technique for Mistuned Bladed-Disks," AIAA Paper 94-1640, 35th AIAA/ASME Structures, Structural Dynamics and Materials Conference, Hilton Head, South Carolina, April 1994. Also, submitted for publication to the *ASME Journal of Vibration and Acoustics*, 1994.