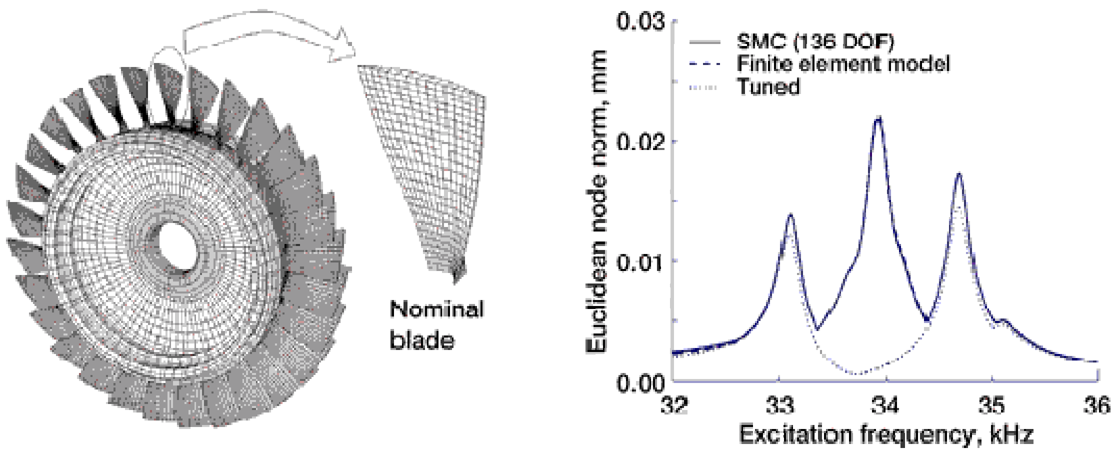
Reduced-Order Blade Mistuning Analysis Techniques Developed for the Robust Design of Engine Rotors

The primary objective of this research program is to develop vibration analysis tools, design tools, and design strategies to significantly improve the safety and robustness of turbine engine rotors. Bladed disks in turbine engines always feature small, random blade-to-blade differences, or mistuning. Mistuning can lead to a dramatic increase in blade forced-response amplitudes and stresses. Ultimately, this results in high-cycle fatigue, which is a major safety and cost concern. In this research program, the necessary steps will be taken to transform a state-of-the-art vibration analysis tool, the Turbo-Reduce forced-response prediction code, into an effective design tool by enhancing and extending the underlying modeling and analysis methods. Furthermore, novel techniques will be developed to assess the safety of a given design. In particular, a procedure will be established for using eigenfrequency curve veerings to identify "danger zones" in the operating conditions--ranges of rotational speeds and engine orders in which there is a great risk that the rotor blades will suffer high stresses. This work also will aid statistical studies of the forced response by reducing the necessary number of simulations. Finally, new strategies for improving the design of rotors will be pursued. Several methods will be investigated, including the use of intentional mistuning patterns to mitigate the harmful effects of random mistuning, and the modification of disk stiffness to avoid reaching critical values of interblade coupling in the desired operating range. Recent research progress is summarized in the following paragraphs.

First, significant progress was made in the development of the component mode mistuning (CMM) and static mode compensation (SMC) methods for reduced-order modeling of mistuned bladed disks (see the following figure). The CMM method has been formalized and extended to allow a general treatment of mistuning. In addition, CMM allows individual mode mistuning, which accounts for the realistic effects of local variations in blade properties that lead to different mistuning values for different mode types (e.g., mistuning of the first torsion mode versus the second flexural mode). The accuracy and efficiency of the CMM method and the corresponding Turbo-Reduce code were validated for an example finite element model of a bladed disk.

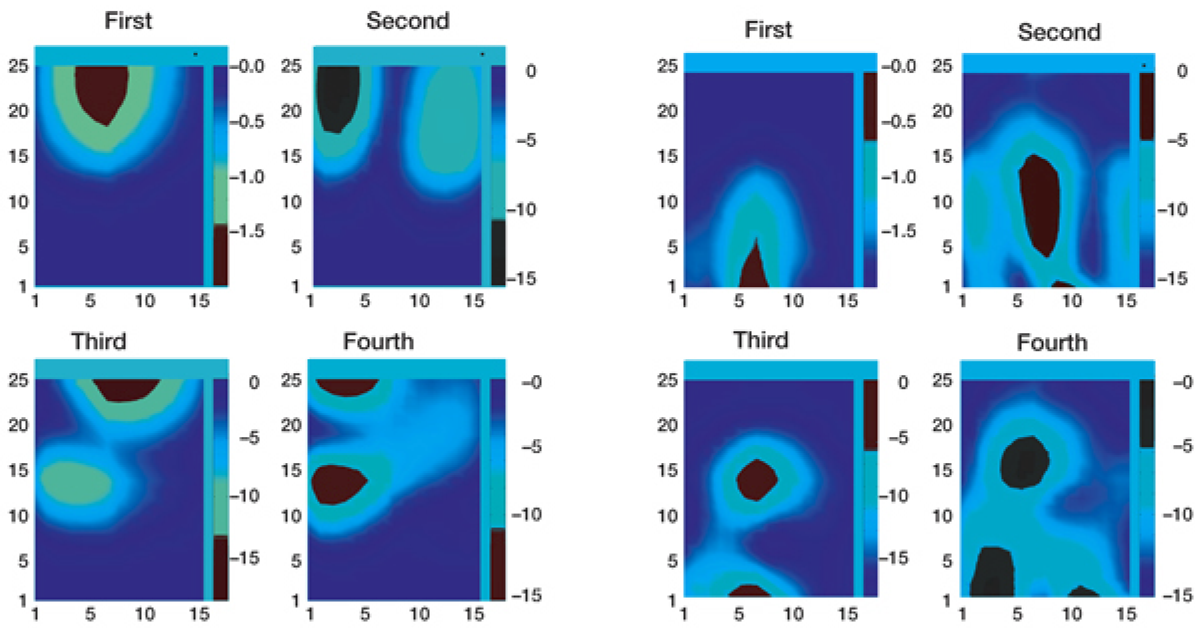


Prototype of a variable-area fan nozzle implementing an overlapping spring leaf assembly, shape-memory alloy wire actuators, and magnetorheological fluid locks. Significant decrease in degrees of freedom (DOF) is shown with the reduced-order modeling technique used in the Turbo-Reduce blade mistuning code. Left: 126,846 DOF in the full finite element model. Right: Forced response for tuned versus mistuned blades; 136 DOF for static mode compensation.

Long description. Left: Finite element model grid. Right: Graph of Euclidean mode norm in millimeters versus excitation frequency in kilohertz for static mode compensation, finite element model, and tuned blades.

Second, SMC was developed for the modeling of large mistuning or geometric blade variations. A generalization of the CMM approach allows the modeling of large blade mistuning (e.g., a rogue blade) by using the so-called attachment modes from component mode synthesis to capture the effects of large mistuning on specified areas of the blade. An example of a bladed disk with one rogue blade was examined. This technique shows promise for modeling systems that incorporate intentional mistuning or geometric changes in the blade design.

Third, a comprehensive investigation was completed on modeling and predicting the effects of mass mistuning (see the following images). Traditionally, mass mistuning has been ignored in favor of simpler models incorporating only eigenvalue or stiffness mistuning. It was found that, relative to stiffness mistuning, mass mistuning widens the range of mistuned natural frequencies, and it also leads to a smaller response at lower frequencies and a greater response at higher frequencies for a given blade mode family. It was determined that the modal power of the blade modes is a metric that indicates the strength of mass mistuning. Furthermore, it was shown that a sensitivity analysis can be used to map the variation of local blade properties to the mass or stiffness mistuning parameters used in the methods and the associated Turbo-Reduce code.



Effect of local blade property mistuning on natural frequencies: sensitivity maps showing the first through fourth natural frequencies. Left: Local mass mistuning. Right: Local stiffness mistuning.

Fourth, enhancements and significant improvements were made in the Turbo-Reduce code for reduced-order modeling and analysis of mistuned bladed disks. The efficiency was increased, and the amount of computer memory needed to run the code was greatly reduced by improving the matrix storage and manipulation schemes used in the code. Enhanced models and simulation options for mistuning were implemented, including improved handling of mass mistuning based on the findings of the mass mistuning study mentioned earlier.

Fifth, key observations were made on frequency veering analysis for identifying critical operating conditions. It was observed that the calculation of continuous natural frequency curves provides physical insight because the actual nodal diameter modes are sampled points on the continuous curves. Furthermore, it was determined that the location of the nodal diameter modes relative to the frequency veerings indicates the relative amount of disk and blade participation in the vibration, and thus provides important information on the design: the strength of the interblade coupling, the sensitivity to mistuning, and possible effects of design changes. This work was performed under a grant by University of Michigan researchers in collaboration with NASA Glenn Research Center researchers.

Reference

1. Bladh, R.; and Pierre, C.: Component-Mode-Based Reduced Order Modeling Techniques for Mistuned Bladed Disks--Part I: Theoretical Models. J. Eng. Gas Turbines Power (ASME Paper 2003-GT-0360), vol. 123, no. 1, 2001, pp. 89-99.

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