Engineering Applications of Artificial Intelligence 67 (2018) 187–196

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

Automated eigenmode classification for airfoils in the presence of fixation uncertainties

Ivo Martin *, Dieter Bestle

Brandenburg University of Technology Cottbus-Senftenberg, Chair of Engineering Mechanics and Vehicle Dynamics, Siemens-Halske-Ring 14, 03046 Cottbus, Germany

ARTICLE INFO

Keywords:
Eigenmode
Classification
Neural network
Principle-component analysis

ABSTRACT

Automated structural design optimization should take into account risk of failure which depends on eigenmodes, since eigenmode shapes determine failure risk by their characteristic stress concentration pattern, as well as by their specific interaction with excitations. Thus, such a process needs to be able to identify eigenmodes with low error rate. This is a rather challenging task, because eigenmodes depend on the geometry of the structure which is changing during the design process, and on boundary conditions which are not clearly defined due to uncertainties in the assembly and running conditions. The present investigation aims to find a proper classification method for eigenmodes of compressor airfoils. Specific data normalization and data dependent initialization of a neural network using principle-component directions as initial weight vectors have led to the development of a classification and decision procedure enabling automatic assignment of proper uncertainty bands to eigenfrequencies of a specific eigenmode shape. Application to compressor airfoils of a stationary gas-turbine with hammer-foot and dove-tail roots demonstrates the high performance of the proposed procedure.

1. Introduction

Lifetime improvement of gas-turbine airfoils can be achieved through risk minimization of high-cycle fatigue (HCF), which requires minimizing the excitation risk of critical eigenmodes. Sources for eigenmode excitation can be self-induced cyclic pressure fluctuations (flutter) or engine-order excitations such as pressure wakes of other airfoils and installations (forced response), see Campbell (1924). In order to determine if an excitation will actually cause resonance and failure, would require the prediction of stress levels and thus, displacement amplitudes through the use of time-consuming, unsteady coupled flow-structure analyses for all relevant running and installation conditions. In order to reduce the computational effort, Blocher and Fernández (2014) introduced a time-linearized-forced-response analysis. It was incorporated into a structural optimization of a counter rotating fan by Fernández and Blocher (2014) as well as by Aulich et al. (2013). The bolted clevises fixing the blades onto the rotor introduce only little uncertainties w.r.t. stiffness, whereas other fixation types used in gas-turbines such as hammer-foot roots have high fixation uncertainty regarding contact with neighboring blades. For example, the contact at surface A in Fig. 1 can be fully restricted or negligible. These uncertainty margins of the system's stiffness result in eigenfrequency bands rather than discrete eigenfrequencies. Using the time-linearized-forced-response approach to analyze fixation conditions between full and no contact with sufficient resolution is computational too expensive.

Other authors try to avoid intersections between resonance and excitation frequencies (self induced excitations, i.e., flutter as well as engine order excitations) in general. For example, Seppälä and Hupfer (2014) performed automated topological optimization of a turbine guide-vane with the constraint that none of the eigenfrequencies of the first five eigenmode shapes are allowed to decrease below given reference values during optimization. But this need for a valid reference does not allow application to the general case of automated design improvement starting from an infeasible design. Pugachev et al. (2014), automatically optimized the eigenfrequencies of a compressor blade where their process requires a baseline design and goals for the desired eigenfrequencies. Such an approach cannot be applied to automated design development either, due to the required user guidance. Astrua et al. (2012), suggested an optimization process that automatically shifts the first eight eigenfrequencies of a compressor blade away from resonance with engine orders, but without the need for a valid reference design. They also introduced uncertainty margins for their prediction of the eigenfrequencies, but did not calculate those from the designs. Such margins of the eigenfrequencies, however, may be predicted by the consideration of possible extrema in fixation and temperatures as

* Corresponding author.
E-mail addresses: ivo.martin@b-tu.de, ivo@martin-erkner.de (I. Martin), bestle@b-tu.de (D. Bestle).

https://doi.org/10.1016/j.engappai.2017.09.022
Received 1 March 2017; Received in revised form 18 August 2017; Accepted 22 September 2017
0952-1976/

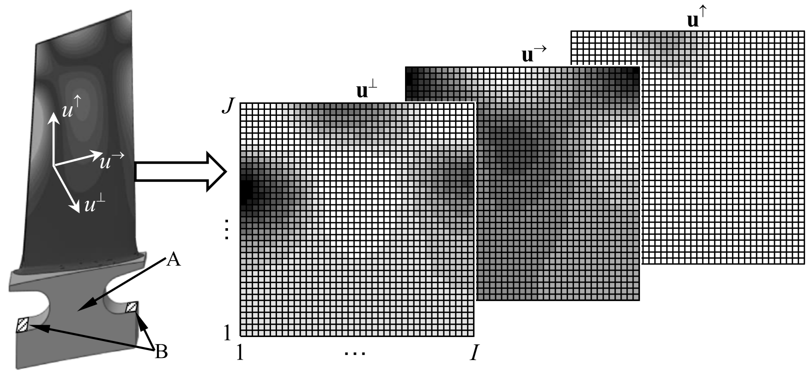

Fig. 1. Airfoil with hammer-foot root fixation and extracted projection of the characteristic displacement fields.

shown by Fedorov et al. (2010) and Hecker et al. (2011) for mounted blades on a massive rotor, or by calculating the eigenfrequencies for the lowest and highest possible nodal diameter in case of blades mounted on a disk or blade-integrated disks (blisks), Strehlau and Kühhorn (2010).

Hecker et al. (2011), further introduced a penalty strategy for eigenfrequency tuning and succeeded in shifting the first ten eigenfrequencies of an infeasible design to make it robust against resonance. This penalty strategy assigns individual penalties to the eigenmode shapes depending on the risk of failure and risk of excitation for specific eigenmode shapes, where penalties result from experimental studies and in-service experience. Therefore, the penalty-strategy requires an automated, unambiguous assignment of eigenmode shapes and frequencies (classification) because of the changing order and characteristic of the modes during design changes. Blocher and Aulich (2013), found that the risk of flutter excitation is identical for similar eigenmode shapes, and in order to avoid re-assessment during an automated fan-blade-design optimization, they detected similar modes via the modal-assurance criterion on consistent FE-meshes.

In order to enable classification of eigenmode shapes of arbitrary geometries independently of the FE-mesh by using only the FE-node location information, Martin and Bestle (2016) introduced a method for projecting airfoil surfaces onto standard rectangular squares, Fig. 1. Taking this work further, the first part of the present paper reveals how eigenmode shapes and uncertainty margins behave between loose and tight fixation with special regards to frequency veering. The subsequent parts then investigate how various techniques of pattern recognition (data normalization, dimension reduction and classification) can improve the performance of classification of eigenmode shapes. Finally, both the fixation study and the classification are the basis for a procedure, where eigenmode uncertainty bands are derived for airfoils of an industrial gas-turbine compressor.

2. Influence of fixation uncertainties on eigenfrequency bands

Assigning proper frequency bands for each eigenmode shape of interest requires not only a reliable classifier but also robust decision rules in the case that classification fails to deliver unambiguous results. Therefore, it is necessary to understand the change of eigenfrequencies between the predicted limits w.r.t. the eigenmode shapes. In this section a rotor blade with hammer-foot-root design is investigated because the fixation stiffness of such root designs varies widely which in turn causes significant changes in the shape and order of eigenmodes. The two stiffness extrema are mainly defined as no contact to neighbors at surface A in Fig. 1 (loose) and fixed contact (tight). For the matter of simplicity, the influence of varying temperature is neglected in the study, because it has only secondary effects on eigenfrequencies. For the analysis, instead of friction the fixation uncertainty is assumed to be caused by uncertain stiffness of contact layers, Fig. 2a. Thus, Young's modulus E of the clamping material in the two contact layers is varied between $6 \cdot 10^{-6} E_0$ and the modulus E_0 of the blade material. In order to make the material deformation consistent, the density is varied proportionally as $\rho = \rho_0 E/E_0$. The displacements at the surfaces A (now outer surfaces of contact layers) and B in Fig. 1 are fixed in all directions, respectively. Further information on the remainder finite-element model is given by Martin and Bestle (2016).

Fig. 2b shows the change of eigenfrequencies w.r.t. Young's modulus, where regions below the fourth and above the 13th eigenfrequency are omitted for clarity. Obviously, several regions of frequency veering appear, where neighboring eigenfrequencies come close and then veer away without crossing. The reason for this behavior is the partial coupling of vibration modes, and the fact that some modes react more dynamically to the stiffening of the system than others. This phenomenon was described by Leissa (1974) as: "a dragonfly one instant, a butterfly the next, and something indescribable in between". Although eigenfrequency curves may not cross, corresponding eigenmode shapes may interchange. From this point of view, tracking of eigenmode shapes must be reinterpreted according to Fig. 2c, where the naming convention is as follows: a mode counter is followed by mode specifier B for bending, C for chord-wise bending, T for torsion, H for higher-order, S for stiff-wise-bending mode, and M for mixed mode (no unambiguous shape character); e.g., 1B is the 1st bending mode. The first issue that becomes apparent is that stronger mode coupling leads to higher eigenfrequency changes between loose and tight limits (e.g. 1H and 3H). In particular, the 1H mode always has high changes as it couples easily with torsion, bending, and chord-wise-bending modes. Furthermore, eigenfrequency changes are associated with changes in the order of eigenmode shapes.

Another issue is that eigenmode shapes like 3T may disappear between the upper and lower limit of fixation, or they only appear between these limits and thus remain undetected such as 4T. The latter case cannot be considered in a design process unless this extensive study is run for each blade design, which would increase the optimization time unacceptably. In the case that an eigenmode shape cannot be traced from one bound to the other, the definition of the corresponding eigenfrequency band depends on the eigenmode shape (more details in Section 7).

3. Normalization of eigenmode data

The correct automated assignment of eigenfrequency bands depends on the quality of classifying eigenmode shapes for lower and upper stiffness limits, where classification means to establish borders between clusters of members of different categories. In the present case, the categories are the fundamental eigenmode shapes and the members are the corresponding eigenvectors, composed of nodal displacements as a result of a FE modal analysis. The purpose of data normalization as the first step in the classification procedure is to enhance separation between the clusters.