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Model updating of rotors supported on journal bearings

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ABSTRACT

Heavy power-plant rotors are generally supported on journal bearings. However, hydrodynamic actions in journal bearings generate spin speed-dependent stiffness and damping forces, which induce instability beyond a spin speed limit called the stability limit speed. The presence of other rotating forces such as due to internal friction may further decrease the stability limit speed. Therefore, identification of journal bearing parameters and other rotating damping forces is important. This work extends Inverse eigen-sensitivity method to update a finite element model of a rotor-shaft system to identify journal bearing parameters and internal friction. Eccentricity ratio and coefficient of shaft material damping are updated in this process to identify bearing model and internal friction force at any speed. Updating of eccentricity ratio to identify journal bearing coefficients as proposed in this work is a novel approach that eliminates the need to update eight bearing coefficients per bearing and hence helps in effective parameterization in the model updating process.

1. Introduction

The journal bearings are generally used to support heavy rotor-shafts of power plant machinery (Vance [1], Rao [2]). The coefficients of journal bearings are functions of parameters like clearance, oil viscosity, and spin speed of the rotor-shaft. The fluid film forces acting on the journal are both conservative and dissipative in nature. These forces cause asymmetry in the stiffness and damping matrices due to the anisotropic as well as cross coupled terms in the matrices, where one of the cross coupled stiffness terms becomes negative above certain speed causing instability (Rao [3]). The journal bearings are characterized by eight bearing coefficients (four stiffness and four damping coefficients for each bearing) (Rao [2], Muszynska [4]). These bearing coefficients are generally not known and need to be identified. Identification of these bearing coefficients has been attempted in this work through the process of finite element model updating.

Finite element model updating techniques are used to adjust selected parameters of finite element models in order to make the models compatible with experimental data. Broadly, the model updating methods are classified into direct and iterative methods. Direct methods were first to emerge and initially these methods were developed to update undamped finite element models (Baruch [5], Baruch and Bar-Itzhack [6], Berman and Nagy [7]). The direct methods update the mass, stiffness and/or damping matrix such that they reproduce the measured data exactly. However these methods suffer from the drawback that the structural connectivity is generally not maintained and the suggested corrections are not physically meaningful. Very little literature is seen in the area of model updating of rotors. A direct updating method for damped gyroscopic systems using constrained minimization approach is recently proposed by Yuan and Guo [8], where the authors have updated the stiffness, damping and gyroscopic matrices.

Iterative methods provide flexibility of selecting the updating parameters apart from overcoming the shortcomings of the direct methods. Minimisation of an objective function forms the basis in the iterative methods. The objective/error/penalty function in this case is composed of the difference between experimental and analytical eigen-data (eigenvalues or eigenvectors

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Nomenclature

All the notations and abbreviations are defined wherever they appear in the paper; however some more frequently appearing terms are written here also:

$\lambda_{r,j}$	Eigenvalue sensitivity in rth mode with respect to jth updating parameter
$\Delta\mathbf{q}$, $\Delta\mathbf{q}_R$	Objective function in complex and real domain respectively
$\mathbf{S}$, $\mathbf{S}_R$	Sensitivity matrix in complex and real domain respectively
$\mathbf{b}$	Vector of fractional correction factors to updating parameters in an iteration
μ, ε, c	Oil viscosity, eccentricity ratio and clearance for journal bearing respectively
η_v	Coefficient of viscous form of rotor-shaft material damping
$\mathrm{Re}(\lambda)$, $\mathrm{Im}(\lambda)$	Real and imaginary part of eigenvalues respectively
IM, RM, UM	Initial, Reference and Updated Finite Element Models respectively
rF, rB	rth forward and rth backward modes respectively

or both) or the frequency response function. A linear expression of the actually non-linear error function is obtained after linearizing the experimental data (eigenvalues, eigenvectors or frequency response functions) about the analytical values of the parameters to be updated. The iterative methods using eigenvalue and eigenvector are termed as Inverse Eigen-Sensitivity Methods (IESM), whereas those using Frequency Response Functions (FRF) are termed as Frequency Response Sensitivity Method (FRSM). An investigation to update stiffness and damping coefficients of bearings supporting a rotor from a few measured frequency response functions was made by Arruda and Duarte [9]. However, the method was demonstrated by updating spin speed independent bearing coefficients with the help of a numerical example. An iterative method based on constrained optimization is also proposed by Modak et al. [10].

The use of eigen-sensitivity for analytical model updating in an iterative process was first proposed by Collins et al. [11]. In IESM, the rate of change of eigenvalues and eigenvectors with respect to updating parameters is used to define a sensitivity matrix. The expressions for these derivatives for undamped system have been given by Fox and Kapoor [12]. Nascimento & Caldiron [13] worked to estimate the stiffness of rotor support by sensitivity analysis. However, damping estimation was not reported in their work and at the same time the authors did not include the effects of gyroscopic moments and circulatory forces in the updating process. Feng et al. [14] presented a method to update finite element models of rotor-shafts by combining Genetic Algorithm and Simulated Annealing methods of optimization, however, effect of rotor spin speed was not taken into account. Rotor-shaft-bearing systems are generally non-self-adjoint by nature due to the gyroscopic and circulatory forces. To solve the problems of non-self-adjoint systems, one needs to use the state space models of equations of motion. The eigensolution and their derivatives for the equation of motion of non-self-adjoint systems consist of complex numbers. To obtain the derivatives of eigenvalues and eigenvectors in state space the work of Plaut and Huseyin [15], and Adhikari and Friswell [16] may be referred to. This work is based on IESM and uses the sensitivities of eigenvalues in writing the sensitivity matrix. The expressions for sensitivities of eigenvalues are obtained after following Plaut and Huseyin [15].

Journal bearings are characterized by eight bearing coefficients per bearing to represent stiffness and damping terms. Closed form expressions for these bearing coefficients are usually obtained by using “Reynolds equation” for specific cases based on short and long bearing assumption. To calculate the coefficients of finite journal bearings, researchers usually resort to numerical solution of the Reynolds equation. Researchers e.g., Smith [17], Rao [2], Friswell et al. [18] among others, have given theoretical derivations to obtain the bearing model in terms of four stiffness (two direct and two cross coupled) and four damping (two direct and two cross coupled) coefficients for the specific cases. These bearing coefficients are functions of eccentricity ratio of the journal and therefore instead of selecting the bearing coefficients, the eccentricity ratio of the journal is considered in this work as the updating parameter. This helps in minimizing the number of updating parameters in the model updating process and hence helps in effective parameterization in the model updating process. Identification of journal bearing coefficients by IESM has not been reported within the literature surveyed so far. Therefore, the same has been proposed in this work for a rotor system supported on short journal bearings. The approximation of short journal bearings gives closed form expressions for bearing coefficients in terms of eccentricity ratio of the journal. Similar closed form expressions can also be obtained based on long bearing assumptions. A comparison of the uses of short and long hydrodynamic journal bearings has been given in the book by Harnoy [19], where the author mentioned about wide use and successful performance of ‘short bearing’ approximation in various machines such as automotive engines.

The rotor-shaft systems supported on journal bearings may be unstable beyond a spin speed limit, called the Stability Limit Speed (SLS) when the tangential force caused by viscosity of the fluid becomes strong enough to nullify the stationary damping forces. The SLS may further reduce due to the presence of internal friction forces caused by rotor-shaft material damping and friction forces in bolted and riveted joints, which all contribute to the generation of the tangential force. Therefore, correct identification of such forces is also important along with the identification of the journal bearing parameters. The work by Tondl [20] shows that the stability limit speed for rotors decreases under combined effect of factors causing instability, e.g. in case of rotors with internal friction mounted on elastic foundation or rotors with oil film bearings supported on elastic foundations. Recent work by Chouksey et al. [21] shows that the reduction in stability limit speed of the rotor system is considerable under the combined influence of fluid film forces and rotor shaft material damping and the extent by which the stability limit speed decreases depends on coefficient of shaft material damping.