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An equation decoupling approach to identify the equivalent foundation in rotating machinery using modal parameters

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ABSTRACT

A correct modelling of rotor-bearing-foundation-system (RBFS) can provide effective rotor balancing and fault diagnostics, therefore, optimise the operating efficiency of the rotating machinery. One major modelling difficulty is to identify the equivalent foundation, which reproduces the same vibration responses over the operating speed range, when substituted for the actual foundation in the RBFS. This paper introduced an identification technique, which utilised the foundation vibration data excited by the existing rotor unbalance, to identify the equivalent foundation using modal parameters. The technique identified the modal parameters of each vibration modes independently by decoupling the modal analysis equations, thereby simplifying the identification procedure. In the illustrative example, the equivalent foundation of a numerical RBFS was identified. When substituted for the actual foundation, the equivalent foundation satisfactorily predicted the system unbalance response and the response prediction was still robust when using the noise corrupted data for the identification. Hence it is concluded that the proposed foundation identification technique is likely to be applicable in practice.

1. Introduction

A sufficiently accurate foundation model is an invaluable asset for rotor dynamics as the dynamic behaviour of a rotating machinery is significantly affected by its supporting structure or foundation [1]. Providing a correct equivalent foundation model, one can effectively diagnose the faults in a rotor-bearing-foundation-system (RBFS), including rotor unbalance [2–4], rotor misalignment [5,6], rotor crack [7], etc. Hence, the techniques to identify the foundation model are of practical interest.

For the supporting structure of existing rotating machinery installation, the foundation model usually need to be identified with the rotor in situ since the rotor removal is usually difficult and costly. A promising approach for such modelling uses the motion measurements of the rotor and foundation at selected points to identify the equivalent foundation [8], defined as a foundation which, when substituted for the actual foundation, reproduces consistent vibration behaviour of the RBFS over the speed range of interest.

There are two common models for the equivalent foundation identification. The first model identifies the system matrix parameters [9,10], which are the elements in mass, damping and stiffness matrices. This model requires solving linear equations of motion for all system matrix elements simultaneously. The solving procedure for system matrix model is

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Nomenclature

$\mathbf{A}$	quasi-modal matrix $=(\mathbf{\Phi}^{-1})^{\mathrm{T}}$; $a_{jk}=$ elements of $\mathbf{A}$	$\tilde{\mathbf{Q}}$	amplitude of modal displacement vector
$\mathbf{c}$	modal damping matrix; c_k = modal damping of the kth mode	$\tilde{\mathbf{x}};\tilde{\mathbf{X}}$	displacement vector; amplitude thereof
$\mathbf{C}$	diagonalisable system damping matrix	$\boldsymbol{\lambda}$	eigenvalue matrix $=\mathbf{m}^{-1}\mathbf{k}$; $\lambda_k=k$th eigenvalue $=\omega_k^2$
$\tilde{\mathbf{f}};\tilde{\mathbf{F}}$	excitation force vector; amplitude thereof	$\boldsymbol{\zeta}$	damping parameter matrix $=\mathbf{m}^{-1}\mathbf{c}$; $\zeta_k=k$th diagonal element of $\boldsymbol{\zeta}$
$\mathbf{I}$	identity matrix	$\boldsymbol{\xi}$	damping ratio matrix $=(2\boldsymbol{\omega})^{-1}\boldsymbol{\zeta}$; $\xi_k=k$th diagonal element of $\boldsymbol{\xi}$
$\mathbf{k}$	modal stiffness matrix	$\mathbf{\Phi}$	system modal matrix; Φ_{jk} = elements of $\mathbf{\Phi}$;
$\mathbf{K}$	system stiffness matrix	$\boldsymbol{\varphi}$	matrix of combined terms ($\boldsymbol{\varphi}^{\mathrm{T}}=\mathbf{m}^{-1}\mathbf{\Phi}^{\mathrm{T}}$); φ_{jk} = elements of $\boldsymbol{\varphi}$;
$\mathbf{m}$	modal mass matrix; m_k = modal mass of the kth mode	$\boldsymbol{\omega}$	natural frequency matrix; $\omega_k=k$th natural frequency
$\mathbf{M}$	system mass matrix	Ω	excitation frequency

usually straightforward; however, the number of unknowns is normally large. The second model identifies the modal parameters [11–14], which normally include the natural frequencies, mode shape elements, modal masses and damping ratios. The modal parameter model contains less number of unknowns in the solving procedure; however it requires solving nonlinear equations.

In our earlier research, we developed an identification procedure to identify the modal parameters of equivalent foundation, using as input data the displacements of the foundation and forces transmitted to the foundation at the bearing supports [15]. Under laboratory environment, the foundation displacements at any given rotor operating speed can be measured via accelerations by accelerometers; however the foundation excitation forces need to be determined indirectly. One possible approach is to estimate the excitation forces relying on the knowledge of rotor and bearing models [10,16]. The other promising approach, instead, rely on an accurate dynamic model of the rotor and the existing rotor unbalance [17]. However, the unbalance state is generally unknown, so one requires motion measurements at the same speeds for both the original unbalance state and a subsequent unbalance state when a known unbalance is added; and these motion measurements need to be subtracted. In either approach, one needs to measure the absolute motion of the rotor at the bearing connection points. Consequently, the acquisition of foundation excitation forces is not considered to be a problem at this stage.

In our previous identification procedure, we developed a technique to decouple the modal analysis equation and solved for the modal parameters of each vibration mode independently [15]. The decoupling process effectively reduced the number of unknowns, and therefore simplified the solving procedure. However, in our previous identification procedure, the damping effect was ignored, the computing program was not comprehensive and the noise analysis was not carried out precisely. In this paper, the identification procedure will be further enhanced and evaluated to cater these issues. The enhanced procedure will be applied to identify the equivalent foundation of a damped flexibly supported flexible foundation block via numerical experiment.

2. Identification theory

Fig. 1 presents the schematic of a general RBFS. As can be seen, an unbalanced rotor is running in bearings, mounted on a flexibly supported flexible foundation.

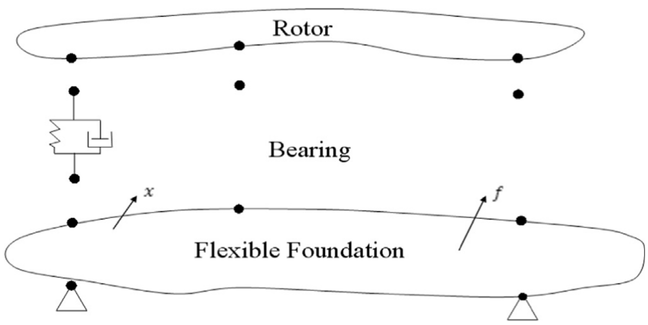

Fig. 1. Schematic of general RBFS with flexible foundation.