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Dynamic balancing of super-critical rotating structures using slow-speed data via parametric excitation

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A R T I C L E I N F O

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A B S T R A C T

High-speed machinery is often designed to pass several “critical speeds”, where vibration levels can be very high. To reduce vibrations, rotors usually undergo a mass balancing process, where the machine is rotated at its full speed range, during which the dynamic response near critical speeds can be measured. High sensitivity, which is required for a successful balancing process, is achieved near the critical speeds, where a single deflection mode shape becomes dominant, and is excited by the projection of the imbalance on it. The requirement to rotate the machine at high speeds is an obstacle in many cases, where it is impossible to perform measurements at high speeds, due to harsh conditions such as high temperatures and inaccessibility (e.g., jet engines).

This paper proposes a novel balancing method of flexible rotors, which does not require the machine to be rotated at high speeds. With this method, the rotor is spun at low speeds, while subjecting it to a set of externally controlled forces. The external forces comprise a set of tuned, response dependent, parametric excitations, and nonlinear stiffness terms. The parametric excitation can isolate any desired mode, while keeping the response directly linked to the imbalance. A software controlled nonlinear stiffness term limits the response, hence preventing the rotor to become unstable. These forces warrant sufficient sensitivity required to detect the projection of the imbalance on any desired mode without rotating the machine at high speeds. Analytical, numerical and experimental results are shown to validate and demonstrate the method.

1. Introduction

The main cause for vibration in rotating structures is “imbalance” which is a common term to describe the effect of minute manufacturing imperfections and deviations of the mass center from the rotation axis. While the structure is rotating, the imbalance gives rise to rotating forces whose effect on individual modes of vibration is proportional to the projection of the imbalance axial distribution on each mode. The structure's response is composed of a superposition of all mode shapes (eigenvectors), where indeed each mode is excited by the projection of the imbalance on the individual mode [1,2].

Imbalance is routinely compensated for by adding (or removing) small correction masses to the structure at pre-defined axial locations. These corrective masses are placed such that their radial and angular locations eliminate the effect of imbalance on all the vibration modes within the relevant speed range. These corrective masses are computed solely from measured vibrations during operation in a so called “balancing process” [3–6]. High speed rotors are usually balanced using

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Nomenclature

a_j	Amplitude of the response of the *jth* mode
A_j	Response of the *jth* mode
$\mathbf{C}$	Damping and gyroscopic matrix
$\mathbf{D}$	Damping matrix
D_i	Differentiation operator w/r to time scales i
$\mathbf{f}_{ib}$	Imbalance force vector
$\mathbf{f}_m$	Modal imbalance force vector
$\mathbf{f}_{co}$	Correction masses force vector
Δf_m	Modal trial mass
$\Delta\mathbf{f}_{ib}$	Trial mass vector
$\tilde{\mathbf{f}}_m$	Modal imbalance force vector at trial run
$\mathbf{f}_{nl}$	Nonlinear force vector
$\mathbf{G}$	Gyroscopic matrix
i	$\sqrt{-1}$
$\mathbf{I}$	Identity matrix
k_p	Parametric excitation's stiffness (pumping amplitude)
$k_{pa,\min}$	Minimal required pumping amplitude
$\mathbf{K_p}(t)$	Time dependant stiffness matrix
$\mathbf{K}$	Stiffness matrix
k_3	Cubic stiffness constant
$\mathbf{M}$	Mass matrix
$\mathbf{q}$	Vector of degrees of freedom
$S_\bullet$	Sensitivity of the response to $\cdot$
t	time
α	angular location of trial mass
β_j	Response phase of the *jth* mode
Γ	Modal stiffness matrix
ε	Small non-dimensional number
$\boldsymbol{\phi}_n$	n^{th} mode shape
$\boldsymbol{\Phi}$	Mass normalized modal matrix
φ	phase
$\boldsymbol{\eta}$	vector of modal degrees of freedom
σ	Detuning parameter
σ_{opt}	Optimal detuning parameter
ω_n	Natural frequency of the *nth* mode
Ω	Speed of rotation
ψ_j	Response phase of the *jth* mode
ζ_n	Damping ratio of the *nth* mode

either the “Influence Coefficient Method”, “Modal Balancing” or the “Unified Balancing Approach” [3–11]. The calculation of the correction masses using the aforementioned procedures is based on measuring the imbalance response close to critical speeds, where the vibration levels and sensitivity are sufficiently high. Usually, the balancing procedure requires the rotor to be spun at the entire anticipated operating speed range during normal service [5].

The requirement to spin the structure at its entire operating speed range is a major obstacle in many cases. Frequently, reaching high rotation speeds involves conditions that do not enable measurements of the imbalanced response (e.g., jet engines where operating conditions involve very high temperatures and hazardous environmental conditions surrounding the rotor). The technical challenges often lead to one of the following:

a. A conservative over-design, trying to keep the critical speeds well above the operating speed.
b. A compromise on the balancing procedure, by using commercial balancing machines [6,12,13], which are incapable of rotating at sufficiently high speeds (e.g., small Jet engines rotate at 100,000 rev/min, while balancing machines are normally limited to 3000 rev/min.). A commercial balancing machine calculates two correction masses that cancel the reaction forces while spinning the rotor at a low speed, assuming that the rotor is rigid [3–6]. Although rigid rotor balancing is a very simple and straightforward procedure, it cannot identify the projection of the imbalance on high speed flexible modes. In fact, in some cases rigid rotor balancing can even increase the projection of the imbalance on high speed related flexible modes [5,11].
c. Damping elements (e.g., squeeze film, magnetic [14,15]) are proposed as a common design alternative for poorly balanced rotors, these add weight and often unacceptable complexity.