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Swept sine testing of rotor-bearing system for damping estimation

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ABSTRACT

Many types of rotating components commonly operate above the first or second critical speed and they are subjected to run-ups and shutdowns frequently. The present study focuses on developing FRF of rotor bearing systems for damping estimation from swept-sine excitation. The principle of active vibration control states that with increase in angular acceleration, the amplitude of vibration due to unbalance will reduce and the FRF envelope will shift towards the right (or higher frequency). The frequency response function (FRF) estimated by tracking filters or Co-Quad analyzers was proved to induce an error into the FRF estimate. Using Fast Fourier Transform (FFT) algorithm and stationary wavelet transform (SWT) decomposition FRF distortion can be reduced. To obtain a theoretical clarity, the shifting of FRF envelope phenomenon is incorporated into conventional FRF expressions and validation is performed with the FRF estimated using the Fourier Transform approach. The half-power bandwidth method is employed to extract damping ratios from the FRF estimates. While deriving half-power points for both types of responses (acceleration and displacement), damping ratio (ζ) is estimated with different approximations like classical definition (neglecting damping ratio of order higher than 2), third order (neglecting damping ratios with order higher than 4) and exact (no assumptions on damping ratio). The use of stationary wavelet transform to denoise the noise corrupted FRF data is explained. Finally, experiments are performed on a test rotor excited with different sweep rates to estimate the damping ratio.

1. Introduction

Frequency response function of rotors can be determined by employing both random and deterministic signals as input excitations. The input signal waveforms include individual or combined periodic signals like multi-sine input [1], harmonic signals like stepped-sine input, transient inputs like swept-sine and impulse excitation and random inputs [2]. Peeters [1,3] estimated the FRF of a rotor bearing system by multi-sine excitation with random phase. Muszynska and Bently [4] addressed the frequency swept rotating input excitation to identify fluid force models in rotors equipped with fluid film bearings. When compared to pseudo-noise excitations, FRF measurements using sine sweeps as excitation signals show significantly higher immunity against distortion and time variance. Swept sine testing is an optimal choice between testing time and amplitude of excitation level needed for testing large rotor bearing systems.

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Nomenclature

A_{max}	maximum acceleration response at $\omega=\omega_{am}$ (for acceleration response) or at $\omega=\omega_{dm}$ (maximum displacement response)
C	damping of rotor system
$\mathbf{F}(\omega)$	generalized force component
$\mathbf{F}(i\omega)$	fast Fourier transform of $F(\omega)$
K	stiffness of rotor system
M	mass of the rotor system
$n(t)$	generated noise signal
N_D	normally distributed random variable
me	unbalance in (kg m)
$r=\frac{\omega}{\omega_n}$	ratio of excitation and natural frequency of the rotor bearing system
$r_d=\frac{\omega}{\omega_{dm}}$	ratio of excitation frequency and frequency at which the maximum displacement amplitude occurs (ω_{dm} – angular acceleration effected resonance frequency).
t	time (s)
t_{max}	time required for the rotor to reach maximum amplitude(s)
$x(t)$, $y(t)$	displacement response in x, y directions
$\mathbf{y}(i\omega)$	fast Fourier transform of output displacement response in y direction

Greek and Roman symbols

α	constant acceleration of rotor (rad s^{-2})
ϕ	phase angle of unbalance excitation force
ζ_S	simulated (or assumed) damping ratio
ζ_C	damping ratio estimated by classical bandwidth method
ζ_E	damping ratio estimated by exact solution
ζ_T	damping ratio estimated by third-order approximation solution
ω	excitation frequency (rad s^{-1})
$\omega_{1,2}$	half-power bandwith points (at amplitude $A=0.707A_{max}$)
ω_{am}	damped natural frequency corresponding to maximum acceleration response
ω_{dm}	damped natural frequency corresponding to maximum displacement response
ω_n	undamped natural frequency of the rotor bearing system

Abbreviations

FRF	frequency response function
FFT	fast Fourier transform
HPBW	half-power bandwith method
SWT	stationary wavelet transform
SNR	signal to noise ratio (in db – decibels)

Although a multi-sine excitation with random phase provides the required testing characteristics, the design weakness and possible active vibration control improvements can be identified from the FRF obtained by a swept sine excitation [4]. In a rotor bearing system, it was identified by Hassenpflug et al. [5] that if a rotor-bearing system is accelerated quickly through its critical speed, then the amplitude of vibration due to unbalance forces can be reduced. This rapid acceleration of rotor through a critical speed is achieved by choosing an optimal sweep rate (angular acceleration), which is a good tradeoff between amplitude and the testing time. FRF was estimated by a synchronous tracking filter [5,6], whereas Lee [7] used Co-quad analyzers. However, Gloth and Sinapius [8] theoretically proved that the swept sine FRF for a general sdof system obtained using Co-quad analyzers will lead to inaccurate identification and mentioned that tracking filters or vectrometers will also yield the same results. The FRF obtained through these methods leads to a distortion in the FRF. It was also mentioned by Gloth and Sinapius [8] that the degree of distortion will depend on the damping present. A lower damping leads to higher distortion of the FRF output. On the other hand, if the damping is high (say $\zeta=0.1$–0.3), then the FRF obtained by these methods will provide a near accurate FRF estimate, but the damping ratio of $\zeta=0.1$ to 0.3 is out of the application range of the rotors. In any common rotating machinery, damping ratio is always less than 0.08 [9]. The test rotor used by Hassenpflug et al. [5] was a lightly damped rotor with damping ratio ($\zeta=0.0088$) and thus the FRF estimated using a synchronous tracking filter is distorted. In the present work, the FRF for a rotor bearing system subjected to swept sine excitation is presented without using Co-quad analyzers, tracking filters or Hilbert transforms. Gloth and Sinapius [8] modified the recommendation of the ISO 7626 standard part II [10] for swept sine analysis of single degree of freedom systems.

Reduction in the maximum response amplitude (active vibration control) of a rotor crossing the resonance can be achieved by (1) decreasing the unbalance forces, or (2) by providing external damping, or (3) by achieving stiffness symmetry (if possible), or (4) by choosing an optimum angular acceleration. A note worthy point made by [5,6] and Lee [7] is that the amplitude reduces with increase in the angular acceleration (sweep rate) of the rotor bearing system. This is because the input excitation with higher angular acceleration will have higher spectral energy. Unlike rotor systems subjected to steady loads, in a rotor subjected to swept sine unbalance loads the increase in angular acceleration leads to a shift of FRF envelope towards right in the frequency domain. This phenomenon can be observed if one compares the half-power bandwidth region for different angular acceleration values of an FRF. This phenomenon of shifting of peaks can be