Mechanical Systems and Signal Processing 107 (2018) 137–148

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

An interval precise integration method for transient unbalance response analysis of rotor system with uncertainty

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ARTICLE INFO

Article history:
Received 3 May 2017
Received in revised form 15 January 2018
Accepted 18 January 2018

Keywords:
Transient response
Rotors
Precise integration
Uncertainty
Interval analysis

ABSTRACT

A non-intrusive interval precise integration method (IPIM) is proposed in this paper to analyze the transient unbalance response of uncertain rotor systems. The transfer matrix method (TMM) is used to derive the deterministic equations of motion of a hollow-shaft overhung rotor. The uncertain transient dynamic problem is solved by combing the Chebyshev approximation theory with the modified precise integration method (PIM). Transient response bounds are calculated by interval arithmetic of the expansion coefficients. Theoretical error analysis of the proposed method is provided briefly, and its accuracy is further validated by comparing with the scanning method in simulations. Numerical results show that the IPIM can keep good accuracy in vibration prediction of the start-up transient process. Furthermore, the proposed method can also provide theoretical guidance to other transient dynamic mechanical systems with uncertainties.

1. Introduction

High speed and heavy power are the development directions of modern rotating machineries. Transient unbalance response analysis is a crucial and indispensable part in rotor dynamic researches because rich information is contained in the start-up or other speed varying process. Many works can be found on the evaluations of rotor transient dynamic behaviors during the past few decades. Bouaziz et al. [1] studied the transient behaviors of an active magnetic bearings-rotor system with angular misalignment using the Newmark numerical method. To reduce the transient imbalance vibrations in rotating machines, Kim and Na [2] designed a new ball-type automatic balancer to improve the performance of traditional ones. The nonlinear response of rub effects in rotor system was investigated by lots of researchers [3–6]. Zapoměl et al. [7] analyzed the transient behaviors of a flexibly supported rigid rotor considering unbalance and damping of short magnetorheological squeeze film dampers. Crack and misalignment effects in rotor dynamic characteristics are frequently investigated [8,9]. Other aspects including clearance [10], base motions [11], damping ratio identification [12] and viscoelastic properties [13] were also studied.

The common feature of the above works is that only deterministic models were considered. However, due to manufacturing and assembly errors, material dispersion and changes in working conditions, uncertainty exists inevitably in rotor systems. In order to obtain reasonable evaluations of transient characteristics, it is highly recommended that uncertainty should be taken into consideration. Presently, the probabilistic methods have been intensively studied and widely employed in

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https://doi.org/10.1016/j.ymssp.2018.01.031
0888-3270/

uncertain rotordynamics. Didier et al. have done many profound researches [14–16] in which rotor dynamic response is approximated by Fourier series and the Polynomial Chaos Expansion (PCE). A comparative study was carried out by Dourado et al. [17] for uncertainty quantification in rotating systems. Focused on the local nonlinearity, Sinou et al. [18] studied the stochastic nonlinear response of an uncertain flexible rotor system. The vibration signatures in diagnosis of chordal crack were verified to be still dominant in the presence of uncertainties [19]. Furthermore, an insightful study of the influence of the expansion order for the polynomial chaos on an asymmetric rotor was conducted [20]. Based on experimental data, Faverjon et al. [21] used the PCE for model validation of a stochastic damped structure with the measurement uncertainties. Jacquelin et al. [22] extended the PCE for representing the response of dynamical systems with mixed random and fuzzy variables. Murthy et al. [23] studied the influence of nonparametric stochastic uncertainties on dynamic characteristics at low rotating speeds. Gan et al. [24] used Monte Carlo method to analyze the sensitivity of the first order critical speed to uncertain parameters. It should be pointed out that probabilistic methods are applicable only when the precise parameter probability distributions are given. However, as frequently encountered, the complete statistic information of uncertain parameters is often not available. In practical, on the other hand, the varying ranges of parameters are easier to define which can be modeled by unknown-but-bounded interval variables. Qiu et al. [25,26] have carried out plenty of studies on interval uncertain structural dynamics using Taylor expansion and perturbation techniques. Qi and Qiu [27] further proposed a collocation interval analysis method based on the Chebyshev polynomials to cope with the overestimation problem in Taylor series based algorithms. Wu et al. [28,29] introduced the Chebyshev inclusion function into multibody mechanical problems and high accuracy and efficiency were achieved. Moreover, it is not restricted to small uncertainties compared with Taylor series and has excellent controlling in the wrapping effect. It has been used to solve uncertain dynamic problems such as gear systems [30]. Up until now, few researches apply interval methods to rotor transient dynamic analysis. Ma et al. [31,32] studied the dynamic response of rotors using perturbation method, Taylor expansion and the interval modal superposition method.

Another dilemma encountered in transient dynamic research is the accuracy and stability problems of numerical integration methods such as Newmark-β and Runge-Kutta methods. Very small integration step is required to obtain reasonable results occasionally and these methods are not capable of dealing with singular or ill conditioned matrices. Zhong [33,34] proposed the PIM for dynamic response calculations, which can get exact solution at each time step. It has been proved that it is unconditionally stable and its precision is independent of step length [35]. Very wide applications of PIM can be found for problems governed by constant coefficient differential equations [36,37] and it has been successfully applied to rotordynamics [38]. Further, some applications in time-varying problems emerged based on modified PIMs [39,40]. Yue [41] extended PIM to time varying structures with rheonomic transition matrices and implemented Magnus expansion [42] to compute the exponential matrix. It is shown that it possesses high accuracy and efficiency. Yet, it has not been applied to uncertain rotordynamics.

In this work, we are devoted to introducing interval analysis into the uncertain transient problem of an overhung rotor system and the IPIM method is proposed by coupling with the modified precise integration method. The hollow shaft rotor system and the derivation of the deterministic equations of motion are illustrated in Section 2. The proposed IPIM method is explained in detail in Section 3. Based on the procedure above, numerical results are given for the rotor system and some discussions are made in Section 4. At last, conclusions are summarized in Section 5.

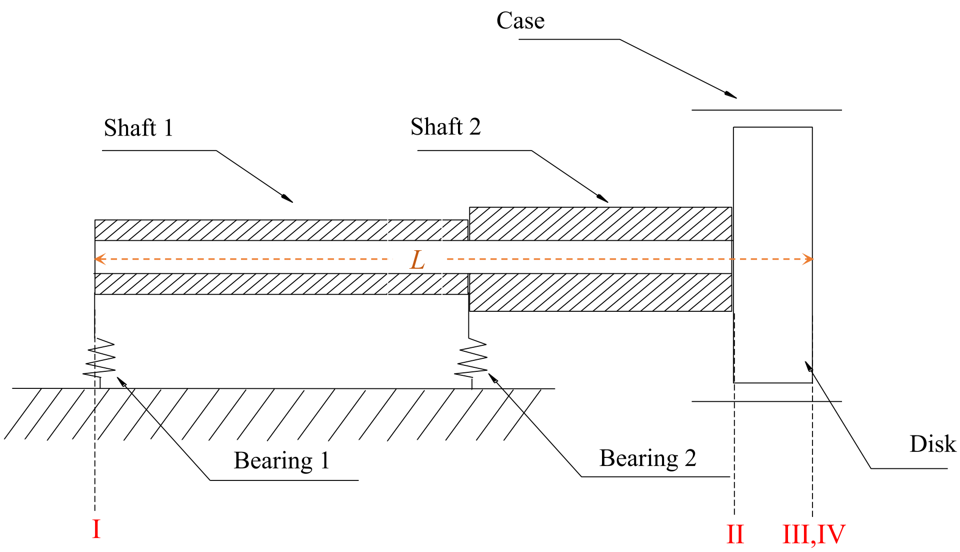

Fig. 1. Schematic diagram of the casing rotor. (I: left end of the rotor, II: left cross-section of the disc, III: right cross-section of the disc, IV: right end of the rotor.)