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Non-linear suspension of an automatic ball balancer

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ABSTRACT

This study investigates the effects on ball positioning because of the non-linear suspensions of an automatic ball balancer (ABB) installed in a rotor system. A complete dynamic model of the ABB, focusing on the non-linearity of the suspensions, is presented. The elastic behaviour of these suspensions is assumed to be well characterised by equivalent non-linear springs. Herein, two Duffing-type non-linear springs are considered: stiffness-softening and stiffness-hardening. Four types of asymptotic solutions that represent the ball positions at steady state are obtained by employing the method of multiple scales. The stabilities of all four types of solutions were found using Floquet theory. In contrast to the perfectly balanced solutions (Type I), the other solution (Type II) is affected by non-linear stiffness suspension. After properly designing the avoidable level of non-linearity, the balancing balls of the ABB still resided at the positions required to reduce the expected vibrations in the steady state. Numerical simulations were performed to validate the theoretical results. The results were also used to predict the level of residual vibration, and design guidelines that would guarantee the desired performance of the ABB for high-precision applications were formulated.

1. Introduction

Imbalances are the standard cause of vibrations in high-speed rotating equipment. To offset rotor imbalance, off-line balancing methods are commonly used in industrial applications. However, if the imbalance varies during operation, it cannot be eliminated only by off-line balancing methods. The automatic ball balancer (ABB) is a typical example of a passive-type system. Although the ABB is effective in reducing vibrations, it still has consistency issues according to previous works. The ABB, which consists of free-running balls inside races, can almost completely eliminate radial vibrations via the concept of counterbalancing. This is based on the fact that as the spindle speed of a rotor exceeds the resonant frequency, the balls inside the race are driven to the opposite of the imbalance by the centrifugal and normal forces created by rotor rotation. Indeed, significant counterbalancing can be achieved via this mechanism.

Thearle [1,2] presented an early analysis of various types of balancing systems and found ball-type balancers to be superior to other types due to low friction, low cost, and ease of implementation. Majewski [3] found the negative effects of ball-rolling resistance, race eccentricity, and external vibrations on the rotor/balancer system at steady state. Rajalingham et al. [4] were the first to include the contact friction of the balancing balls in a model. Huang et al. [5] introduced a simple stick-slip model and illustrated the unavoidable rolling friction between the balancing balls and the race flange actually deterred the balls from residing precisely at the desired positions. Lu and Hung [6] explored a theoretical model with a three-ball ABB was constructed. Rodrigues et al. [7] presented an analysis of a two-plane ABB for rigid rotors. DeSmidt [8] developed the dynamics and stability of an imbalanced flexible shaft equipped with an ABB. Liu and Ishida [9] presented the vibration suppression method utilising the discontinuous spring characteristics together with an ABB. The non-linearity will influence the amplitude and the phase angle of vibration. Therefore, non-linearity is one of the key factors responsible for the inconsistency and ball mispositioning of an ABB. Ehyaei and Moghaddam [10] developed a system of unbalanced flexible rotating shafts equipped with *n* ABBs where the unbalanced masses were distributed along the length of the shafts. Green et al. [11] presented the non-linear bifurcation analysis of a two-ball automatic dynamic balancing mechanism for eccentric rotors.

These previous studies only adopted linear stiffness models for the suspension, neglecting the profound influence of suspension non-linearity. However, there is non-linearity in many mechanical systems and spring components. Chao et al. [12] was the first to explore the non-linear dynamic effects of damping washers on the performance of an ABB installed in optical disc drives.

This paper proposes a theoretical study of the effects of non-linear suspension on the ball positioning for an ABB. This non-linearity influences the amplitude and phase angle of suspension vibration, which is considered as one of the key factors that affect ball positioning when using an ABB. A complete dynamic model of

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