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# A new hybrid observer based rotor imbalance vibration control via passive autobalancer and active bearing actuation

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ABSTRACT

Many researchers have explored the use of active bearings, such as non-contact Active Magnetic Bearings (AMB), to control imbalance vibration in rotor systems. Meanwhile, the advantages of a passive Auto-balancer device (ABD) eliminating the imbalance effect of rotor without using other active means have been recently studied. This paper develops a new hybrid imbalance vibration control approach for an ABD-rotor system supported by a normal passive bearing in augmented with an AMB to enhance the balancing and vibration isolation capabilities. Essentially, an ABD consists of several freely moving eccentric balancing masses mounted on the rotor, which, at supercritical operating speeds, act to cancel the rotor's imbalance at steady-state. However, due to the inherent nonlinearity of the ABD, the potential for other, non-synchronous limit-cycle behavior exists resulting in increased rotor vibration. To address this, the algorithm of proposed hybrid control is designed to guarantee globally asymptotic stability of the synchronous balanced condition. This algorithm also incorporates with a "Luenberger-like" observer that continuously estimates the states of a balancer ball circulating around within ABD. In particular, it is shown that the balanced equilibrium can be made globally attractive under the hybrid control strategy, and that the control power levels of AMB are significantly reduced via the addition of the ABD because the control is designed such that it is only switched on for the abnormal operation of ABD and will be disengaged otherwise. Moreover, unlike other imbalance vibration control applications based upon ABD such as rotor speed regulator [21,22], this approach enables the controller to achieve the desirable performance without altering rotor speed once the rotor initially reaches the target speed. These applications are relevant to limited power applications such as in satellite reaction wheels, flywheel energy storage batteries or CD-ROM application.



## 1. Introduction

Imbalance vibration is a significant concern for all rotor dynamic systems and engineering problems associated with them. Therefore, with this concern, how to suppress the effect of imbalance vibration is also a critical issue for ensuring reliable and efficient operation of these systems. One elegant approach to deal with this issue is based on so-called auto-balancing devices (ABD). These are a special class of passive devices with freely moving eccentric masses, which naturally adjust to cancel the

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rotor's imbalance at certain operating condition (speed). The merit of this device is the ability to compensate for imbalance changes without requiring the power, sensors, or a control system.

One early experimental study of automatic balancing was conducted by Thearle [1], who characterized the dynamics of a planar ball ABD under various imbalance levels. Further [2], and [3] numerically explored the spinup and steady-state response of planar rotor-ABD system and showed that complete balancing can be achieved by an ABD containing a minimum two balancer masses. Majewski [4], constructed planar equation-of-motion and examined the effects of ball-rolling resistance and runway eccentricity on the rotor-balancer system at steady state. Jinnouchi et al. [5] showed that the planar rotor-ABD system provides excellent balancing at the supercritical speed but leads to amplified vibration at sub-critical speeds. Lindell [6], installed ABD in a hand-held grinding machine to reduce the unbalance vibration. Although the ABD possesses the advantage to passively deal with the imbalance vibration of ABD-rotor system at certain condition [7], and [8] investigated the behavior of a rotor-autobalancer system and noted the co-existence of stable synchronous and sub-synchronous limit-cycles which caused high vibration. DeSmidt [9] derived the mathematical model of flexible shaft based rotor system fitted with ABD and addressed all possible fixed equilibriums of given system.

Inoue, T., Ishida [10], also presented the analytical solution for the limit-cycle condition of single-plane ABD-rotor system and validated the analysis with the experimental outcomes. Furthermore [11], investigated three different limit cycle behaviors for the planar dual-ball automatic balancer with the symmetric support; a pure oscillatory periodic motion, a pure-rotary periodic motion, and a compound-rotary periodic motion.

Recently, Jung and DeSmidt [12,13] have presented analytical approaches to unstable limit cycle condition using harmonics-based solutions for single-plane ABD-rotor systems and flexible shaft/ABD/rotor systems, respectively. This limit-cycles is described as non-synchronous behavior where the balancer masses (or balls) in ABD do not reach the stable synchronous equilibrium relative to a rotating rotor and are continuously rotating with almost the natural frequency of system [7–13] so that it can lead high vibration amplitude. Furthermore, instead of symmetric bearing [14], dealt with the non-synchronous limit cycle behavior of ABD-rotor supported by asymmetric bearing and found the multiple limit cycles and more complicate coexistences at supercritical speeds.

Another common way to deal with the imbalance vibration issue is the active control or active balancing found in Refs. [15] and [16] using the magnetic type of actuator/bearing (AMB) or the actively controlled journal bearing. Also [17], provided the holistic review of active balancing and vibration control of rotating machine and [18] shows the application of AMB into segmented drive shafts. Furthermore, Kang [19] addressed LMI based AMB control approach for imbalance rotor system. Also [20], proposed gain phase modifier (GPM) incorporated with feedback control to achieve a precise control of imbalance rotor. Basically, AMB generates the electromagnetic field through the coil inside it and maintain a certain level of air gap/clearance between a shaft and the coil by controlling the magnetic force induced by the arranged coils. Although this active control can ensure the global stability of system and be adaptive for the change of operating environment, this mean definitively requests a certain amount of control power to meet a desired vibration level. Therefore, in this paper, we investigate that the hybrid interaction between the ABD and the AMB governed by the active control law for an imbalance rotor supported by a passive normal contact bearing can produce better performance compared to the rotor system equipped with only ABD and normal contact bearing as well as reduce the control power consumption of AMB relative to the case actively controlled via solely AMB without both ABD and passive bearing. Specifically, AMB compensates the deficiencies of ABD system such as the limit-cycles condition and its own limited capacity. Simultaneously, the assistances of both ABD and passive bearing can reduce the consumption of AMB control force by partially or entirely cancelling the imbalance effect/force because the hybrid control strategy proposed here is designed in the sense that the active control of AMB is only switched on for abnormal operating condition of ABD and will be hibernated for the normal situation otherwise. In such way, there will be no control force from AMB if the balancing condition of system is naturally and passively achieved by interaction between a rotor with passive bearing and ABD. Additionally, a "Luenberger-like" observer is employed for continuously estimating the states of ball moving around within ABD, which is demanded by the derived active control law of AMB.

[21,22] addressed the repositioning scheme of the balancer ball in an ABD via a fuzzy-logic based rotor speed regulator. Using the variation of rotor speed from the target speed to the critical speed or vice versa, this approach enforces the ABD-ball into more favorable position (so-called re-positioning) by inducing the motion of balancer ball initially trapped in the less desirable fixed equilibrium position relative to the angular phase of imbalance at the target speed due to the friction between the ABD-ball and the contact surface of ABD racing track. However, there are some applications that the re-positioning of ABD-ball or the destabilization of limit cycle condition is required without changing the rotor speed, such as satellite reaction wheels and flywheel energy storage batteries.

Therefore, by using the advantages of both devices (ABD and AMB) in this hybrid approach proposed here, the imbalance vibration and the nonlinear behavior introduced by ABD can be efficiently and robustly eliminated with no manipulation of rotor speed once the rotor initially reaches the target speed. Therefore, the energy consumption required for repetitively altering the rotor speed is unnecessary here. The contents of paper are followed. In Section 2, the mathematical model of the planar ABD-rotor system supported by AMB and a passive bearing is introduced and the design of observer and the development of hybrid control strategy have been discussed in Section 3. Finally, the effectiveness of proposed technique has been validated through the MATLAB/Simulink simulation.