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Unbalance and resonance elimination with active bearings on a Jeffcott Rotor

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ABSTRACT

In this contribution we have proven theoretically and practically that active bearings are able to eliminate both bearing forces and the resonance of a Jeffcott Rotor system. Active bearings can displace a rotor such that its center of mass always stays in the rotational center. The proposed collocated controller is able to keep this state at any rotational speed, leading to an elimination of bearing forces and resonances. We analytically demonstrated that the closed-loop system is *always* stable, even without knowledge of the rotor's properties. The generalization of the proposed control approach for force-free operation either using displacement or force actuators enables its use for all kinds of active bearings. Moreover, the control approach allows a real time estimation of the rotor's eccentricity. The low parameter count and the unproblematic stability behavior qualify the controller for many applications.

1. Introduction

In the late 19th century, engineers believed a rotating machine could not be operated above its critical speed. Laval was the first to show practically that a rotor can operate beyond this limitation. Although Föppl and Jeffcott published correct explanations for the phenomenon, the Jeffcott Rotor prevailed in the engineering literature [1].

The center of mass never coincides with the center of rotation on real rotors. The resulting eccentricities cause rotor vibrations leading to rotor deflections and bearing forces. Both quantities get especially large when the rotor operates close to a critical speed. They are usually unwanted because they cause material stresses, noise and excessive bearing wear. The standard method to reduce vibrations is balancing, a process in which the rotor's masses are redistributed to keep the rotor's eccentricity reasonably small [2]. Even for balanced rotors, it is usually avoided to permanently operate a rotating machine close to a critical speed.

Active bearings based on electromagnetic actuators have been under heavy development since the 1980s and found applications in industry where conventional bearings might not be feasible. Although stiffness and damping can be adjusted, it is mandatory that the bearing forces caused by unbalance do not exceed the maximum actuator forces to maintain stability. The freedom of implementing different control schemes encouraged scientists to investigate methods to tackle the negative effects of unbalances. A large number of different algorithms emerged, which can be subcategorized in two

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approaches [3]. One approach reduces the rotor displacements, which is indicated when high radial runout precision is required. On the downside, large actuator forces might be necessary to pull the rotor in the desired position [4,5]. In many applications, a perfect radial runout is unnecessary as long as the deflections do not exceed boundaries, for example in turbomachinery. In this case, it is desired to reduce the unbalance-induced bearing forces for a smoother machine operation and less actuator load. These methods reside under a variety of different names, such as Adaptive Autocentering Control [6], Adaptive Forced Balancing [7], Periodic Learning Control [8], Automatic Inertial Autocentering [9], Unbalance Compensation [10], Adaptive Feedforward Compensation [11] and Unbalance Force Rejection Control, a method described in an ISO-Standard [12]. Of all the approaches, two main concepts prevailed. The notch filter approach [13] suppresses the synchronous bearing forces and allows the rotor to rotate around its principal axis of inertia. As a shortcoming, it cannot stabilize the system at critical speeds. In contrast, the adaptive feedforward compensation injects a synchronous harmonic signal into the control system to compensate the unbalance forces [14]. The method can pass critical speeds when the rotational speed is changing slowly, however, stability is not necessarily guaranteed. Additionally, the exact nature of the injected signal and its physical interpretation remain unclear.

Inspired by the offered possibilities of active bearings, researchers started to look for alternatives based on other actuator principles. Palazzolo used piezoelectric actuators in combination with conventional ball bearings to reduce rotor vibrations [15–17]. After the feasibility of his approach was demonstrated, research focused on unbalance compensation. Lindenborn and Hasch were able to reduce bearing forces or rotor displacements in several orders of magnitude using adaptive feedforward compensation [18,19].

A large number of publications deal with unbalance problems and thereby reflect its general importance. Even though researchers tried to unify the approaches by introducing generalized notch filters [20], the connection between filtering and adaptive feedforward control is still obscure. Further the behavior of unbalance compensation in critical speeds is focus of discussion. While some experiments show that unbalance compensation does not work in the mechanical resonance, others show that both forces and displacements can be reduced simultaneously [3]. The practical usefulness of the unbalance compensation methods is further limited as most of them need accurate models and careful system design to work stably and reliably, impeding their field application.

For many years structural engineers treated almost exclusively rotordynamic problems and developed powerful tools to explain the motion of rotors [21]. In fact, the famous Hurwitz criterion for stability analysis originated from a rotordynamic problem [22,23]. On the other hand, the development of active bearings was mainly an achievement of control and electrical engineers. Consequently, control strategies were mainly described using transfer functions and block diagrams, methods which originated in signal theory. Despite the invaluable contribution of these methods for simple mechanical systems, they fail to adequately address rotordynamic questions such as equilibrium conditions, mode shapes or whirl directions. Structural engineers might be able to answer some of these questions but may get overwhelmed by complex concepts like feedforward compensation. We think that a generalizing approach needs to consider control, electrical and structural engineering simultaneously.

In this publication, we found a generalizing explanation for the elimination of unbalance forces on Jeffcott Rotors with active bearings. Our argumentation is based on a careful revision of the underlying kinematics and focuses on statically determinate rotors. Bearings – independent of the technology – keep the rotor in a defined position, maintaining a force equilibrium. In statically determinate systems, bearing reaction forces depend on the rotor load *only*. Current literature often reveals that active bearings *exert* controllable forces on a rotor. This statement contradicts the conditions of static stability. We point out that active bearings can *displace* a rotor without altering the force equilibrium and introduce a bearing displacement vector. The advantage of this approach is the consistent derivation of the equations of motion and its compatibility with structural mechanics. Our control design eliminates bearing reaction forces caused by unbalances. It drives the bearing displacements to keep the center of mass always in the rotational center. Some parts of the controller are defined in rotating coordinates, leading to a comprehensive derivation of the adaptive controller structure. The analysis of the closed-loop system reveals that the controller is able to keep the center of mass in the rotational center even at the speed of the mechanical resonance and that a force-free condition can be achieved at *any* rotational speed. Thus we *prove that active bearings can eliminate the unbalance-induced rotor resonance*. Remarkably, this controller has the property of *unconditional stability*, regardless of the rotor's mass and stiffness. This property even holds for rotational speeds that match the resonance frequency. We *generalize* the control approach for different actuators, which we divide into two groups: Displacement and Force actuators. Displacement actuators have an inherent mechanical stiffness and are capable to support a rotor without additional control efforts. Force actuators, on the other hand, have no inherent mechanical stiffness and need an additional control system to support the rotor. In latter case, the controller must both support the rotor and eliminate the unbalance-induced bearing forces at the same time. We derive control laws for both actuator types, establishing a link between different active bearing principles and show that unbalance elimination is possible for any type. Inspired by the work of Herzog et al. [20], we take advantage of the fact that some controller parts are initially defined in rotating coordinates. The result is not only a simplified implementation of the controller but also allows further system insight: *The controller's state directly represents the eccentricity*. Despite its simplicity, the controller directly enables access to the rotor's balancing condition in physical meaningful units. The favorable stability behavior and the fact that no specific rotor knowledge is required make the controller suitable for industrial applications. The low count of adjustable parameters enables engineers to adjust the controller in the field without the need for an extensive rotordynamic simulation.

We stress that the obtained results are valid for Jeffcott Rotors only and do not consider effects such as gyroscopy, but we are currently working on the generalization for more complex rotor systems.