THE DYNAMICS, STABILITY AND CONTROL OF ROTOR TOUCHDOWN IN ACTIVE MAGNETIC BEARING SYSTEMS

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ABSTRACT

Power generation, gas compression, vacuum generation, and machining are example applications for spinning rotors. Higher power density is enabled by higher rotational speeds. Rotors levitated by active magnetic bearings (AMBs) allow such increase in speed because they have low torque resistance and the rotor dynamics are controllable. However, abnormal overload events or transient faults may give rise to a loss of functionality and cause a rotor to come into contact with emergency touchdown bearings (TDBs). The rotor may experience a number of responses ranging over bouncing and rubbing, which may result in excessive vibration at a level that may cause structural damage to the system. An understanding of the mechanisms that drive these persistent nonlinear contact dynamics is important if control strategies to restore contact-free rotor levitation are to be designed and implemented with confidence. This paper will explore the options that are available for AMBs and active TDBs.

1 INTRODUCTION

Contact-free operation of rotor/active magnetic bearing (AMB) systems is well known [1]. However, problems may arise when rotor/stator contact occurs and these are reviewed in [2] with respect to the rotor dynamic responses. In AMB-levitated rotor systems, rotor drop is a clearly defined problem. In the absence of AMB functionality, the TDB support characteristics are of importance in achieving a soft landing and acceptable rotor dynamic response during rundown [3]. However, contact induced rotor dynamics may also occur when the AMBs are still functional, hence active control options are also available. A typical layout in Figure 1 shows the AMB coils for the vertical axis, through which electrical currents (i_U, i_L) may be adjusted for levitation control of the rotor and to maintain clearance between the rotor and the AMB. Excessive external influences or faults conditions may cause the rotor to make contact with a touchdown bearing (TDB), which is in place to prevent excessive rotor dynamic excursions. When the rotor is in contact with the TDB, radial (normal) and tangential (friction) forces are introduced into the rotor dynamic behaviour. These forces may be large and may become persistent and undesirable [4, 5]. If control functionality is still available from an AMB or an active TDB, it may be possible to restore the rotor to a desirable contact-free state.

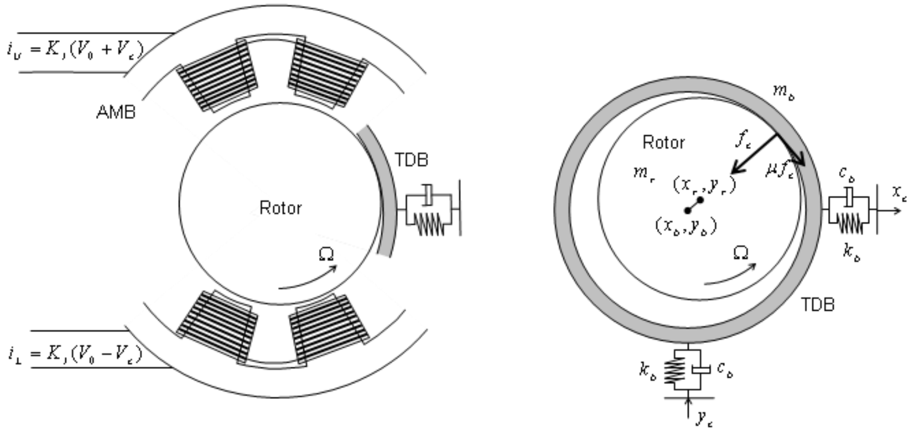

Figure 1. Spinning rotor within an AMB showing possible contact with a TDB.

2 PERSISTENT ROTOR CONTACT MODES

The linearized equation of motion of a rigid rotor (Figure 1) in an AMB having stiffness and damping properties is

$$\ddot{z} + 2\xi\omega_n\dot{z} + \omega_n^2 z = \frac{f_u}{m_r}e^{i\Omega t} - \frac{f_c}{m_r}(1+i\mu)\frac{z}{c_r}, \tag{1}$$

where $z = x_r + iy_r$ is the inertial frame complex displacement, c_r is the radial clearance, μ is a Coulomb friction coefficient, and f_u is the unbalance. In an idealized representation, contacts may be represented by a series of delta function impulses. Between contacts ($f_c = 0$) analytical solutions may be sought that achieve repeatable bounce like motions before and after each contact (see Figure 2, left contact orbit B). Viewed in a synchronously rotating reference frame,

$$w = u_r + iv_r = ze^{-i\Omega t}, \tag{2}$$

orbit B has the loci shown in Figure 2 (right). Figure 2 also shows the completely contact-free

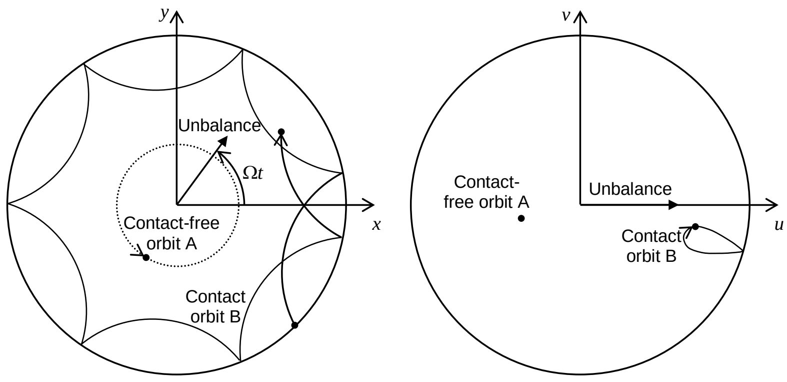

Figure 2. Bistable contact-free (A) and bouncing contact (B) motions in inertial (*x*, *y*) and synchronously rotating (*u*, *v*) frames of reference.

orbit A,

$$z = \frac{f_u}{m_r(\omega_n^2 - \Omega^2 + 2i\xi\omega_n\Omega)} e^{i\Omega t}, \quad w = \frac{f_u}{m_r(\omega_n^2 - \Omega^2 + 2i\xi\omega_n\Omega)}. \tag{3}$$

Figure 2 thus demonstrates an example of bistable responses driven by rotor unbalance. In orbit A, the rotor whirls in a circular contact-free condition within the clearance space of the AMB. In orbit B, a bouncing mode solution is also possible. In the left hand side diagram it is seen that the response of orbit B is lagging slightly behind the rotating unbalance vector, while the orbit A is almost in anti-phase with the unbalance vector. This effect is caused by the ‘hard’ boundary of the TDB, as represented by the delta function contacts. The phases of the orbits are seen more clearly in the rotating frame view of the right hand side diagram in which orbit A is represented by a single point and orbit B becomes a small loop on the TDB boundary.

Numerical simulations may also be undertaken in which the contact forces are represented in terms of Hertzian contact stresses and the TDB is resiliently mounted (Figure 1). These will be more representative of practical applications. Further, the TDB may be simulated in an active mode by imposing displacements (x_c, y_c) through the resilient mounts. Nonetheless, the idealized contact solutions may be used to guide understanding and decide upon appropriate control action.

Persistent contact is problematic since the contact force levels are typically large and in excess of the magnitude of the unbalance force vector. These may cause structural damage to the TDB and/or the rotor. Furthermore, frictional forces at a contact zone will be high, which will induce significant thermal inputs to the TDB and the rotor, resulting in thermal distortion and thermal bending, respectively.

3 OPTIONS TO RESTORE CONTACT-FREE LEVITATION

In this paper, two open-loop feedforward control actions are considered for AMBs and, if available, active TDBs. Their feedforward nature limits any problems that may arise from closed loop feedback.

3.1 Using AMB feedforward action

In this case, synchronous forces are applied through the AMBs to compensate for the unbalance that is driving the rotor dynamic contact. The compensating forces must have the appropriate amplitudes and phases so as to minimise the contact forces, preferably to zero. The control forces may be applied in a ramped manner to reduce transient responses and achieve a smooth re-levitation of the rotor.

3.2 Using TDB feedforward action

In this case, synchronous control forces are applied to the TDBs in order that the contact forces between the rotor and the TDB may be influenced and minimised. Figure 3 shows an example of such control action that restores contact-free levitation.

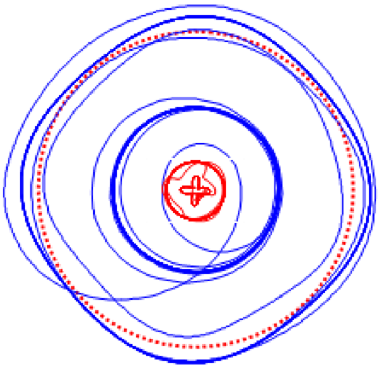

Figure 3. Active TDB motion (red) to induce a rotor out of a persistent rub contact mode (blue). Viewed in an inertial (x, y) frame of reference.

4 CONCLUDING REMARKS

This paper presents the options for restoring contact-free operation in AMB-levitated rotor systems. Without control, the contact rotor-dynamics may persist and become damaging for the components in the system. It is demonstrated that if functionality of the AMBs or active TDBs exists, appropriate control action may reduce contact forces to a level at which they become unsustainable and contact-free levitation follows.

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