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Dynamic Conditions to Destabilize Persistent Rotor/Touchdown Bearing Contact in AMB Systems

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Abstract

It is now common practice to supplement a magnetic bearing with a touchdown bearing to protect the rotor and stator components. Rotor/touchdown bearing contact may arise from rotor drop, caused by power loss or emergency shutdown. This paper considers the control options that are viable when the magnetic bearing is still functional should contact may arise from intermittent faults or overload conditions. The problem is that bi-stable rotor responses are possible, with and without contact. If rotor contact should become persistent, the desirable course of action is to destabilize the rotor response and induce a return to contact-free levitation. In order to achieve this, it is appropriate to gain an understanding of the rotor dynamic behavior. This is determined from analytical and simulated results to reveal suitable control actions. These may be applied through the magnetic bearing control system, or by activating the touchdown bearing through a separate control loop. The issue is that standard control action for a contact-free rotor state will not be appropriate for a rotor in persistent contact since the basic plants to be controlled are significantly different. The required control action must be activated only when contact is detected. The results demonstrate that appropriately phased synchronous forcing could destabilize synchronous forward rub responses. Alternatively, small whirl motions of a touchdown bearing could also be beneficial without disturbing the main magnetic bearing control loop.

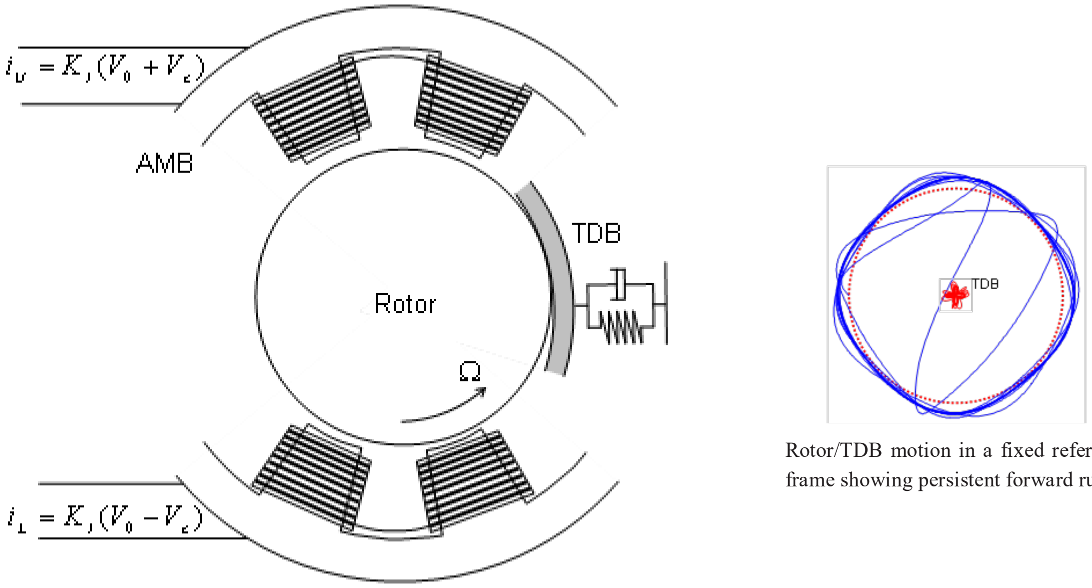
Keywords: Touchdown bearing, rotor contact, rotor rub, dynamic contact conditions, persistent contact.

1. Introduction

The interaction of an active magnetic bearing (AMB) levitated rotor with a touchdown bearing (TDB) has received significant attention is recent years. Clearly, it is important to prevent damage to expensive rotor and stator components with the sacrificial components being the replaceable touchdown bearing and landing sleeve. However, it is beneficial for the touchdown bearing to be designed and operated to have some significant life in order that losses of machine output and downtime are minimized.

The condition involving the loss of levitation or rotor drop is an obvious case to consider and the majority of studies focus on this. The works of Bartha (1988) and Fumagalli et al. (1994) consider theory and experiments for this problem. Larger scale drop tests were initially undertaken by Schmied and Predetto (1992) and Kirk et al. (1993, 1994) and Swanson et al. (1995). Simulation of rotor drop includes the nonlinear study of Foiles and Allaire (1997). The study in this area has continued to bring out the finer details of the rotor dynamic and touchdown bearing responses (Sun et al., 2004; Helfert et al., 2006; Hawkins et al., 2007). Recently, significant further activity has also followed from the ISMB13 and ISMB14 (Janse van Rensburg et al., 2012, 2014; Collins et al., 2014; Denk et al., 2014; Siebke and Golbach, 2014; Siegl et al., 2014; Yang et al., 2014). Further detailed studies include those of Lee and Palazzolo (2012), Anders et al. (2013) and Lahriri and Santos (2013).

The other relevant conditions relate to a fully functional rotor/AMB system, which may experience rotor/touchdown bearing contact in cases involving AMB overload, intermittent faults or shock inputs. The contact events may be transient



Rotor/TDB motion in a fixed reference frame showing persistent forward rub

Fig. 1 Simulation of a rotor making contact with a touchdown bearing (TDB) within a functional AMB.

and the rotor may return naturally to a contact-free levitated state. However, under certain conditions the contact events may persist and become stable unless further control action is taken or other inputs are applied (Keogh and Cole, 2003; Cole and Keogh, 2003). It is desirable to destabilize such persistent contact since it will cause an accumulation of damage and limit touchdown bearing residual life. A number of authors have investigated this problem. Ulbrich and Ginzinger (2006) considered electromechanical actuation of a touchdown bearing, while Cade et al. (2008), Keogh et al. (2008) and Li et al. (2014) implemented piezoelectric actuation of a touchdown bearing.

It is beneficial to have a greater understanding of rotor contact dynamics in order that more appropriate control actions can be applied with a more assured outcome. Rather than direct simulations, which may require many parameter variations, this paper considers analytical expressions to aid the understanding of the contact dynamics. The effects of control actions are also discussed with relevance to implementation.

2. Dynamic simulation showing persistent contact

Figure 1 shows an example of a dynamic simulation of a rigid disk rotor making contact with a touchdown bearing (TDB) within a functioning AMB system. The AMB was configured to have isotropic linearized stiffness and damping characteristics. The rotor had an initial unbalance, low enough to ensure that a contact-free orbit was possible with an orbit radius less that the rotor/TDB radial clearance. The rotational frequency was set to be above that of the AMB levitated rotor. An initial velocity was given to the rotor and the ensuing rotor motion develops into a full forward rub involving persistent contact (right view). The TDB, which is resiliently mounted also experiences motion under the applied contact forces. This single simulation demonstrates that bi-stable rotor responses are possible.

3. Simple force equilibrium

Figure 2 shows synchronous orbits viewed in a synchronously rotating reference frame. The left view is a contact-free case in which unbalance drives the rotor to the orbit point E, which lies within the clearance circle. The phase angle between the force and response is determined from the AMB characteristics. However, it is possible to visualize another case as shown in the right view, which involves rotor/TDB contact. Here, the resultant synchronous force of magnitude f_s, drives the rotor to the point C on the clearance circle, which is in forward synchronous rubbing. This force is the resultant of the normal contact force of magnitude f_c, the unbalance force of magnitude f_u and the friction force of magnitude μf_c, which act in the directions shown in Fig. 2. The relation between (f_u, E) is similar to that between (f_s, C), but the orientation is different. Hence, it is seen how bi-stable responses may exist, one without contact and one

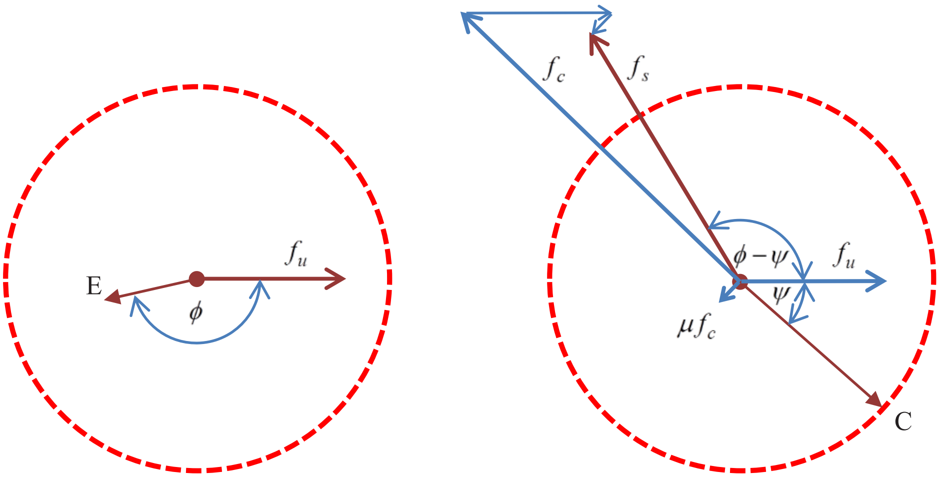


Fig. 2 Synchronous orbits viewed in a synchronously rotating reference frame. The left diagram shows a contact-free orbit E induced by the unbalance force f_u. The right diagram shows how the resultant synchronous force f_s can induce the rub orbit C.

involving contact.

3.1 Steady synchronous rotor motion with/without rub

To examine the influence of these responses it is of interest to consider equations of motion without movement of the TDB. The orbits E and C may be specified by the complex representations,

$$\begin{aligned} z_{E,C} &= x_{E,C} + iy_{E,C} && \text{(in a fixed reference frame)} \\ w_{E,C} &= u_{E,C} + iv_{E,C} = z_{E,C}e^{-i\Omega t} && \text{(in a syncronously rotating reference frame)} \end{aligned} \tag{1}$$

where Ω is the rotational speed. By including the AMB radial stiffness and damping characteristics through a natural frequency ω_n and damping ratio ξ, the equations of motion may be cast in the forms

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

in the fixed frame, or

$$\ddot{w}_{E,C} + (2\xi\omega_n + 2i\Omega)\dot{w}_{E,C} + (\omega_n^2 - \Omega^2 + 2i\xi\omega_n\Omega)w_{E,C} = \frac{f_u}{m} - \frac{f_c}{m}(1+i\mu)\frac{w_C}{c_r} \tag{3}$$

in the rotating frame, where c_r is the radial clearance and $f_c = 0$ for orbit E. When the conditions are steady, the non-contacting orbit of radius r_E is given by

$$w_E = r_E e^{-i\phi} = \frac{f_u}{m(\omega_n^2 - \Omega^2 + 2i\xi\omega_n\Omega)} \tag{4}$$

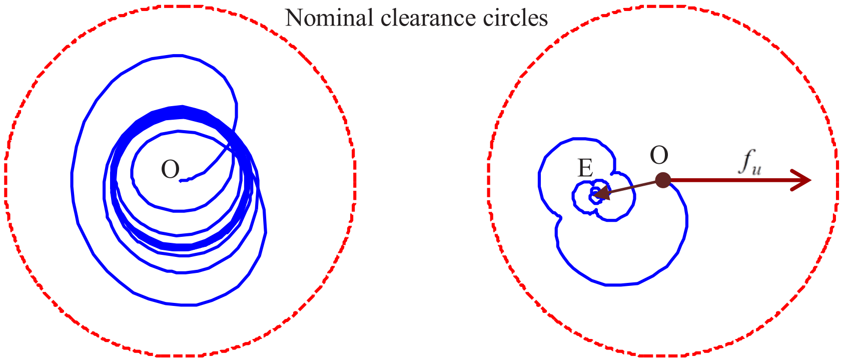
If the rotor is in a steady rub orbit then $w_C = c_r e^{-i\psi}$ and it follows from Eq. (3) that

$$(\omega_n^2 - \Omega^2 + 2i\xi\omega_n\Omega)c_r e^{-i\psi} = \frac{f_u}{m} - \frac{f_c}{m}(1+i\mu)e^{-i\psi} \tag{5}$$

Therefore Eqs (4) and (5), together with the force equilibrium of Fig. 2 give rise to

$$\frac{f_u}{m}\frac{c_r}{r_E}e^{i(\phi-\psi)} = \frac{f_u}{m} - \frac{f_c}{m}(1+i\mu)e^{-i\psi} = \frac{f_s}{m}e^{i(\phi-\psi)} \tag{6}$$

Hence the synchronous driving force amplitude is linked to the synchronous unbalance force amplitude by the orbit radii ratio according to $f_s = f_u c_r / r_E$. Furthermore, the contact force can be derived from Eq. (6) as



(a) (x, y) plot (b) (u, v) plot

Fig. 3 Orbits due to a step change of unbalance of 425 N starting from rest at the center O of the clearance circle. (a) Viewed in an inertial reference frame; (b) Viewed in a synchronously rotating reference frame.

$$f_c = \frac{f_u}{(1+i\mu)}\left(e^{i\psi} - \frac{c_r}{r_E}e^{i\phi}\right) \tag{7}$$

In general this is complex valued. However, if ψ is varied such that

$$\operatorname{Im} f_c = \operatorname{Im}\left\{\frac{f_u}{(1+i\mu)}\left(e^{i\psi} - \frac{c_r}{r_E}e^{i\phi}\right)\right\} = 0 \tag{8}$$

this will indicate that synchronous forward rubbing is possible if also

$$\operatorname{Re} f_c = \operatorname{Re}\left\{\frac{f_u}{(1+i\mu)}\left(e^{i\psi} - \frac{c_r}{r_E}e^{i\phi}\right)\right\} > 0 \tag{9}$$

Ultimately, in contrast with Eq. (4), the rubbing contact satisfies

$$w_C = c_r e^{-i\psi} = \frac{f_s e^{i(\phi-\psi)}}{m(\omega_n^2 - \Omega^2 + 2i\xi\omega_n\Omega)} \tag{10}$$

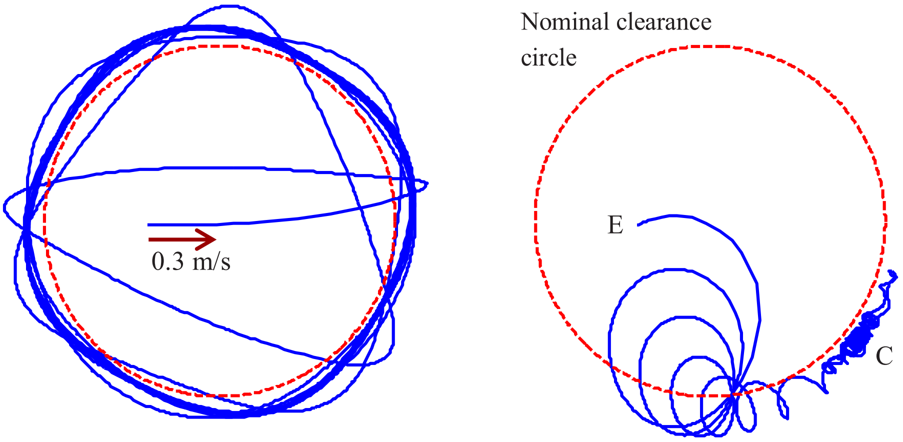
3.2 Transient responses in the synchronously rotating reference frame

Consider the basic case with reference to orbit E. If the unbalance force, f_u, had been applied as a step change at $t=0$, the transient response of the rotor, w_R viewed in the synchronously rotating reference frame from the center of the TDB is

$$w_R = w_E\left\{1 - e^{-\xi\omega_n t}\left(\frac{-\xi\omega_n - i(\Omega+\omega_d)}{2i\omega_d}e^{-i(\Omega-\omega_d)t} - \frac{-\xi\omega_n - i(\Omega-\omega_d)}{2i\omega_d}e^{-i(\Omega+\omega_d)t}\right)\right\} \tag{11}$$

where $\omega_d = \omega_n\sqrt{1-\xi^2}$. In order to evaluate the response, the following data were chosen: $m = 4.25$ kg, $\omega_n = 638$ rad/s, $\xi = 0.086$, $\Omega = 1000$ rad/s, $c_r = 0.4$ mm. Starting at rest from the center O of the clearance circle, the rotor response due to a step change of unbalance from $f_u = 0$ to $f_u = 425$ N is shown in Fig. 3. In the inertial reference from (Fig. 3(a)), the rotor response settles a forward circular whirl of radius 0.166 mm. The view in the synchronously rotating reference frame (Fig. 3(b)) shows the transient response of Eq. (11) before the rotor settles at E.

A direct simulation of the rotor response was then undertaken to induce contact with the TDB. The following data were chosen: $k_B = 6\times10^7$ N/m (TDB radial support stiffness), $c_B = 2500$ Ns/m (TDB radial support damping), $m_B = 0.18$ kg (TDB mass), $\mu = 0.05$. The inner radius of the TDB was 15 mm and the TDB had a steel inner race. The AMB was modeled in a standard manner as an 8-pole type with a magnetic gap of 0.8 mm under PID control so as to give the linearized natural frequency and damping values quoted previously. To induce contact with the TDB, the rotor was given an initial velocity in the $x-$direction of 0.3 m/s. The responses are shown in Fig. 4. The initial bouncing contacts are followed by significant transient activity before the final migration to C. Note that the resilient mounting of

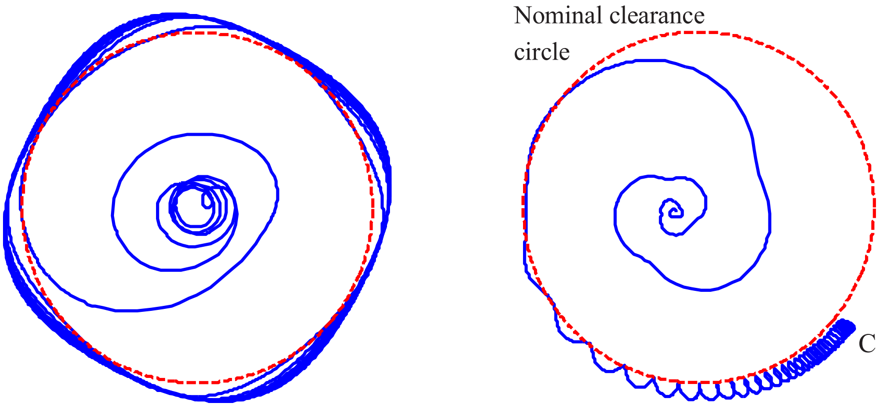


(a) (x, y) plot (b) (u, v) plot

Fig. 4 Orbits due to velocity initial condition of 0.3 m/s on the rotor to the right in the inertial reference frame. (a) Viewed in an inertial reference frame; (b) Viewed in a synchronously rotating reference frame.

the TDB results in the final position of the rotor outside the nominal clearance circle. Also, the nonlinear AMB model with causes C to be a small orbit rather than a single point. Notwithstanding the differences with the idealized analytical forms, C approximates that of Fig. 2.

4. How can the rotor be moved from contact orbit C back to contact-free orbit E?

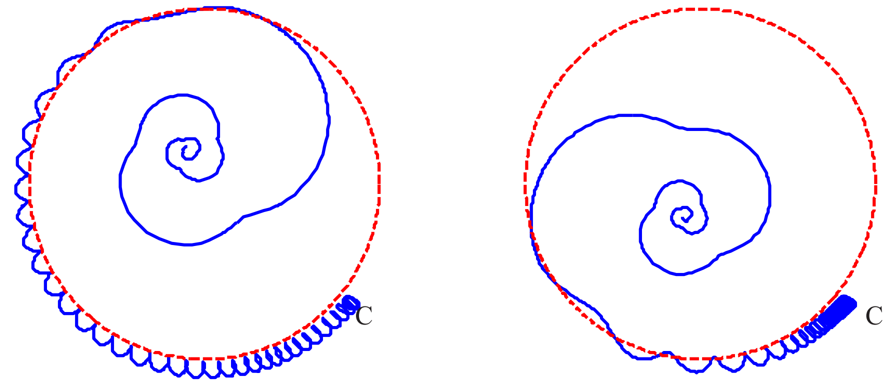


(a) (x, y) plot (b) (u, v) plot

Fig. 5 Orbits due to a rotating synchronous AMB control force at 180 deg phase, ramped from 0 to 270 N over 0.1 s. The rotor recovers from the contact condition C to a contact-free state within the clearance circle.(a) Viewed in an inertial reference frame; (b) Viewed in a synchronously rotating reference frame.

4.1 AMB synchronous control to induce loss of contact

A simple application of a compensating synchronous control force f_{AMB} from the AMB to negate the influence of f_u may suffice to induce loss of contact. However, prior knowledge of the unbalance force f_u may not be available, though some directional inference may be made from the location of C (Fig. 2). It may also be desirable to avoid step-like changes in synchronous control that drive the rotor harder into the TDB. Therefore, Fig. 5 shows a ramp-like change in applied synchronous AMB control force with 180 deg phase, causing loss of contact when is attains an amplitude of 270 N. The effect is to bring the rotor around the TDB from C to a point at which contact is lost. It is not necessary to



(a) 425 N at -150 deg (b) 340 N at 150 deg

Fig. 6 Synchronous (u, v) orbits due to a rotating synchronous AMB control forces at the phase angles shown. The control force amplitudes were ramped from 0 N to the values shown over 0.1 s. The rotor recovers from the contact condition C to a contact-free state within the clearance circle.

apply the compensating AMB synchronous force with a precise knowledge of the phase. Figure 6 shows cases of ±150 deg with loss of contact at 340 N and 425 N, respectively. Figure 7 shows the contact force variation as the AMB force is applied for the case shown in Fig. 6(b).

4.2 TDB control to induce loss of contact

As an alternative to AMB control, similar movements of the rotor from the contact area C are possible through displacements of the TDB, if actuation is available. Figure 8 shows an example simulation leading to recovery of a contact-free rotor. Here the TDB was actuated in a synchronous forward circular whirl of radius 0.1 mm and a phase of 90 deg. This causes the clockwise rotor movement in the synchronous frame that ultimately leads to loss of contact.

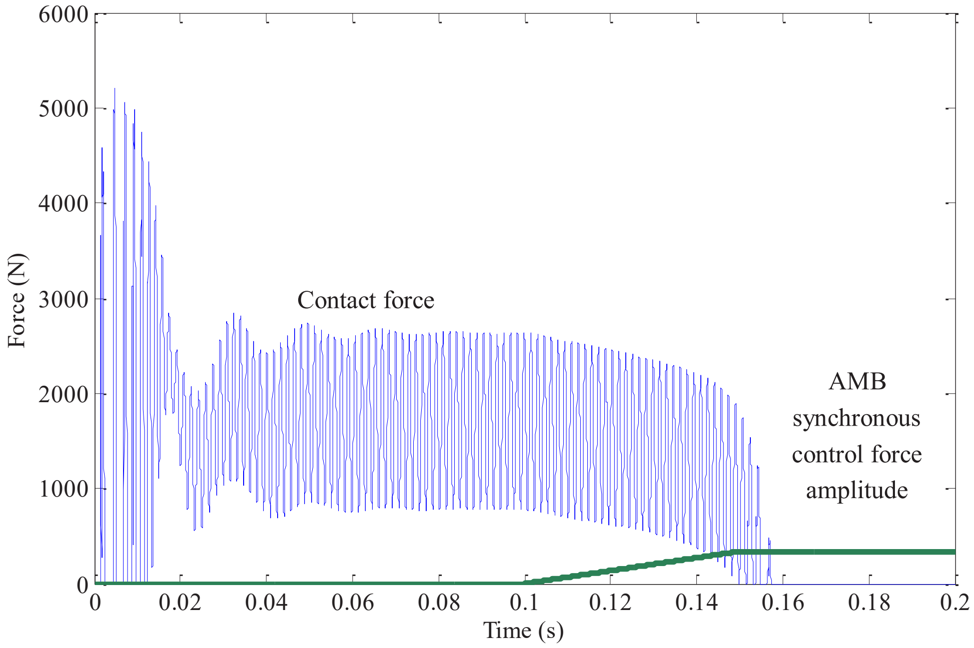
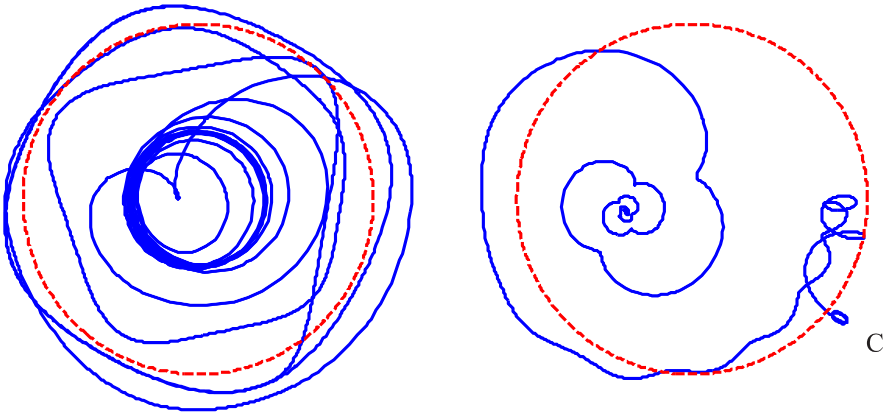


Fig. 7 Contact force f_c initiated by the input velocity shown in Fig. 4. The ramped synchronous AMB control force of Fig. 6(b) was initiated at 0.1 s when the rotor is in the contact state C. Since the contact force reduces to zero, a contact-free state ensues.



(a) (x, y) plot (b) (u, v) plot

Fig. 8 Orbits due to a synchronous TDB displacement of amplitude 0.1 mm applied with 90 deg phase. The rotor recovers from the contact condition C to a contact-free state within the clearance circle.

5. Conclusions

The demonstration of bi-stable rotor responses in a rotor/AMB/TDB system has been made using a rigid disk rotor model. A combination of simulation and analytical expressions were used to show how synchronous forward rubbing may coexist with a contact-free forward whirl under the same rotor dynamic conditions. Significant changes in the phase of the rotor response relative to the unbalance vector may be evident between the bi-stable states. These features are better viewed in a synchronously rotating reference frame in which forward whirl orbits are represented as stationary points.An assessment was then made of the control actions to destabilize a with-contact rotor response, returning it to the contact-free condition. If AMB functionality is still available, one option is to apply open-loop forward synchronous forcing that is phased so as to reduce the driving contact force. However, as soon as the rotor becomes contact-free the AMB synchronous force may be reduced back to zero, otherwise another contact state may arise.

Further control action is also possible if the TDB may be actuated at a fraction of the radial clearance. Forward whirl actuation of the TDB may be used to influence the contact conditions. It may be possible to cause loss of contact, though the analysis and simulations indicate that the phasing of the actuation is important. If applied incorrectly, the actuation may even increase the severity of the contact condition.

Further work is required to assess the full range of rotor dynamic conditions. For example, in addition to rotor rubbing, rotor bouncing contact and backward whirls should also be assessed. Also, multimode responses of a realistic rotor will introduce added complexity to this important problem.

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