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 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 should 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.

Key words: 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 TDB and landing sleeve. However, it is beneficial for the TDB 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 TDB 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). In each of these papers the AMBs are not functional and the primary concern is to achieve safe run-down of the rotor on passive TDBs.

Other relevant operational conditions relate to a fully functional rotor/AMB system, which may experience
rotor/TDB contact in cases involving AMB overload, intermittent faults or shock inputs. The contact events may be
transient 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 TDB 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 TDB. The option of an active TDB offers additional control capability
with the potential to restore contact-free rotor levitation.

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. The new aspect of this paper is that it enables
feedforward control action to be deduced that may destabilize persistent forward whirl rub responses. The control may
be applied either as synchronous forcing through an AMB or as synchronous displacement of an active TDB.

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. In this representation it is assumed that the disk does not tilt within the
AMB/TDB clearance gaps, hence there is no axial component to any contact force. It also follows that the rotor disk does
not experience gyroscopic moments. The TDB of mass $m_B$ is mounted on a radial stiffness, $k_B$, and damper rate, $c_B$,
allowing for displacement components, $(x_B, y_B)$. The rotor inertial frame displacement components are $(x_R, y_R)$ and
for simulations the rotor is represented as a simple disc of mass $m_R$. When contact with the rotor occurs with a normal
contact force, $f_c > 0$, the equations of motion for the TDB are embedded in the complex form

$$m_B \ddot{z}_B + c_B \dot{z}_B + k_B z_B = (1 + i\mu) f_c e^{i\theta}$$

where $z_B = x_B + iy_B$, $\mu$ is the effective coefficient of friction between the rotor and TDB, and
$
\theta = \tan^{-1}(y_R - y_B)/(x_R - x_B)$. The corresponding equations of motion for the rotor are

$$m_R \ddot{z}_R = f_{mu} + ef_{mu} - (1 + i\mu) f_c e^{i\theta} + f_a e^{i\phi}$$

Fig. 1 Simulation of a rotor making contact with a touchdown bearing (TDB) within a functional AMB.
Here, the magnetic bearing is considered to be fully functional with force components \((f_m, f_u)\). \(\Omega\) is the rotor speed and \(f_u\) is the unbalance force magnitude. An eight-pole radial magnetic bearing in a differential driving mode is considered. The magnetic bearing force components, including a simplified saturation limit, are written in the usual form

\[
\begin{align*}
\begin{pmatrix}
2 f_0 & 2 f_0 & 0 & 0 \\
0 & 0 & 2 f_0 & 2 f_0 \\
2 f_0 & 2 f_0 & 0 & 0 \\
0 & 0 & 2 f_0 & 2 f_0 
\end{pmatrix}
\begin{pmatrix}
\tanh(z/c_m) \\
\tanh(z/c_m) \\
\tanh(z/c_m) \\
\tanh(z/c_m)
\end{pmatrix}
\end{align*}
\]

where \(z = x_R\) or \(y_R\). The effective magnetic bearing clearance, \(c_m\), is less than the nominal TDB radial clearance, \(c_r\). The coefficients \(k_m\) and \(k_f\) determine the maximum force capacity and they incorporate the voltage gain of the system. A magnetic bearing controller is assumed to use PID feedback of rotor displacements to set the control voltage \(V_c\). Static forces acting on the rotor will therefore be compensated for by the integral action, hence these are not included in the equations of motion.

Under a Hertzian contact model, the rotor will be in contact with the TDB if

\[
\delta r = \sqrt{(x_R - x_b)^2 + (y_R - y_b)^2} \geq c_r
\]

The circumferential arc length of the contact zone, \(2a\), is related to the normal contact force by

\[
a = \sqrt{4R' f_c / \pi E' l_b}
\]

where \(l_b\) is the axial width. The effective radius, \(R'\), and Young’s modulus, \(E'\), parameters are given by

\[
\begin{align*}
R' &= R_b R_R / c_r \\
1/E' &= (1 - \nu^2)/E_R + (1 - \nu^2)/E_B
\end{align*}
\]

where \(\nu\) denotes Poisson’s ratio. The nonlinear contact force/deflection relation is then contained within

\[
\delta r - c_r = f_c / \pi E' l_b \left( 2 + \ln \frac{4R_b R_R}{a^2} \right)
\]

An inverse numerical procedure may be used to determine the force/deflection relation for use in Eqs. (1) and (2).

The rotor was given 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, data appropriate to Section 3.2. The rotational frequency was set to be above the natural frequency 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 of Fig. 1). 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.

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.
3. Simple force equilibrium

Figure 2 shows synchronous orbits viewed in a synchronously rotating reference frame \((u, v)\) in Fig. 1. 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 using the AMB characteristics under proportional and derivative control. 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 vector resultant of the normal contact force of magnitude \(c_f\), the unbalance force of magnitude \(u_f\) and the friction force of magnitude \(\mu f_c\), which act in the directions shown in Fig. 2.

The relation between \((u_f, E)\) is similar to that between \((s_f, C)\), but the orientation is different. Hence, it is seen how bistable responses may exist, one without contact and one involving contact.

3.1 Steady synchronous rotor motion with/without rub

To examine synchronous responses it is of interest to consider equations of motion without movement of the TDB. The AMB characteristics are also linearized and the contact z one is represented as a line contact. The orbits E and C may be specified by the complex representations,

\[
\begin{align*}
    z_{E,C} &= x_{E,C} + iy_{E,C} \\
    w_{E,C} &= u_{E,C} + iy_{E,C} = z_{E,C} e^{\Delta \omega t} 
\end{align*}
\)

By including the linearized AMB radial stiffness and damping characteristics through a natural frequency, \(n\omega\), and damping ratio, \(\xi\), the equations of motion may be cast in the forms

\[
\begin{align*}
    \ddot{z}_{E,C} + 2\xi \omega n \dot{z}_{E,C} + \omega_n^2 z_{E,C} &= \frac{f_s}{m_R} e^{i \omega t} - \frac{f_c}{m_R} (1 + i \mu) \frac{z_{E,C}}{c_r} \\
    \ddot{w}_{E,C} + (2\xi \omega n + 2\Omega) \dot{w}_{E,C} + (\omega_n^2 - \Omega^2 + 2i \xi \omega_n \Omega) w_{E,C} &= \frac{f_s}{m_R} - \frac{f_c}{m_R} (1 + i \mu) \frac{W_C}{c_r}
\end{align*}
\]

in the fixed frame, or

\[
\begin{align*}
    \ddot{w}_{E,C} + (2\xi \omega n + 2\Omega) \dot{w}_{E,C} + (\omega_n^2 - \Omega^2 + 2i \xi \omega_n \Omega) w_{E,C} &= \frac{f_s}{m_R} - \frac{f_c}{m_R} (1 + i \mu) \frac{W_C}{c_r} \quad (10)
\end{align*}
\]

in the rotating frame, where \(f_c = 0\) for orbit E. The steady, non-contacting orbit of radius \(r_E\) is given by

\[
\begin{align*}
    w_E &= r_E e^{-i \phi} = \frac{f_s}{m_R (\omega_n^2 - \Omega^2 + 2i \xi \omega_n \Omega)} 
\end{align*}
\]

If the rotor is in a steady rub orbit then \(W_C = c_r e^{-i \phi'}\) and it follows from Eq. (10) that

\[
\begin{align*}
    (\omega_n^2 - \Omega^2 + 2i \xi \omega_n \Omega) c_r e^{-i \phi'} &= \frac{f_s}{m_R} - \frac{f_c}{m_R} (1 + i \mu) e^{-i \phi'} 
\end{align*}
\]

Therefore Eqs (11) and (12), together with the force equilibrium diagram of Fig. 2 give rise to

\[
\begin{align*}
    \frac{f_s}{m_R} c_r e^{i(\phi - \phi')} &= \frac{f_s}{m_R} - \frac{f_c}{m_R} (1 + i \mu) e^{-i \phi'} = \frac{f_s}{m_R} e^{i(\phi - \phi')}
\end{align*}
\]

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. (13) as

\[
\begin{align*}
    f_c &= \frac{f_u}{(1 + i \mu)} \left( \frac{e^{i \phi'} - c_r e^{i \phi}}{r_E e^{i \phi}} \right) \quad (14)
\end{align*}
\]

In general this is complex valued. However, if \(\psi\) is varied such that

\[
\begin{align*}
    \text{Im} f_c &= \text{Im} \left\{ \frac{f_u}{(1 + i \mu)} \left( \frac{e^{i \phi'} - c_r e^{i \phi}}{r_E e^{i \phi}} \right) \right\} = 0 \quad (15)
\end{align*}
\]
(16)

\[ \text{Re} \left( f_\epsilon \right) = \text{Re} \left[ \frac{f_u}{(1+i\mu)} \left( e^{i\phi} - \frac{c_\epsilon}{r_E} e^{i\phi} \right) \right] > 0 \]

(17)

\[ w_c = c e^{-i\psi} = \frac{f e^{i(\phi+i\psi)}}{m_\mu (\omega_n^2 - \Omega^2 + 2i\xi_\omega \Omega)} \]

### 3.2 Transient responses in the synchronously rotating reference frame

To provide examples of analytical and simulated responses, data were related to the experimental system shown in Fig. 3. This shows a symmetric rotor that can be levitated by two similar AMBs. To associate with the rigid rotor disk model of Fig. 1, the right hand side half-rotor is considered with the AMB and active TDB.

Consider the basic case with reference to orbit E. If the unbalance force, \( f_u \), had been applied as a step change at

![Nominal clearance circles](image)

**Fig. 4** 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.
\[ t = 0 \] the transient response of the rotor, \( w_R \) viewed in the synchronously rotating reference frame from the center of the TDB is

\[
w_R = w_E \left[ 1 - e^{-\varpi_d t} \left( -\varpi_n - i(\Omega - \omega_d) e^{-i(\Omega - \omega_d)t} - \varpi_n - i(\Omega - \omega_d) e^{-i(\Omega + \omega_d)t} \right) \right]
\]

where \( \varpi_d = \omega_n \sqrt{1 - \xi^2} \). In order to evaluate the response, the following data were appropriate: \( m_R = 4.25 \) 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. 4. In the inertial reference frame (Fig. 4(a)), the rotor response settles to a forward circular whirl of radius 0.166 mm. The view in the synchronously rotating reference frame (Fig. 4(b)) shows the transient response of Eq. (18) 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: \( k_B = 6 \times 10^7 \) 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 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. 5. The initial bouncing contacts are followed by significant transient activity before the final migration to C. Note that the resilient mounting of the TDB results in the final position of the rotor outside the nominal clearance circle. Also, the nonlinear AMB model 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.

### 3.3 Synchronous rotor rub motion under TDB synchronous motion

If a mechanism and control system to impose prescribed TDB motions is available, it is appropriate to assess the rotor dynamic response and investigate whether contact-free conditions may be induced from a rubbing state. Consider the imposed TDB motion to be a forward synchronous whirl:

\[
\begin{align*}
\varpi_B &= r_B e^{i(\Omega + \gamma)} \\
\varpi_R &= r_B e^{i\gamma}
\end{align*}
\]

This would represent a static shift of the nominal clearance circle when viewed in a \( (\mu, \nu) \) plot, for example, Figs 4(b) and 5(b). Write the relative rotor to TDB displacements as

\[
\begin{align*}
\varpi_{RB} &= \varpi_B - \varpi_R \\
\varpi_{RB} &= \varpi_B - \varpi_R
\end{align*}
\]

In the inertial frame, Eq. (9) is modified to
\[ \ddot{z}_R + 2\tilde{\varphi}_n^\prime \dot{z}_R + \omega_n^2 z_R = \frac{f_e}{m_R} e^{i\omega} - \frac{f_c}{m_R} (1 + i\mu) \frac{\tilde{z}_{RB}}{c_r} \]  

(21)

Under steady conditions in the synchronous frame, this transforms to

\[ \dot{w}_{RB} + (2\tilde{\varphi}_n + 2i\Omega)\dot{w}_{RB} + (\omega_n^2 - \Omega^2 + 2i\tilde{\varphi}_n \Omega)w_{RB} = \frac{f_e}{m_R} - \frac{f_c}{m_R} (1 + i\mu) \frac{w_{RB}}{c_r} - (\omega_n^2 - \Omega^2 + 2i\tilde{\varphi}_n \Omega)w_B \]  

(22)

Comparing with Eq. (10), the additional TDB displacement term on the right hand side of Eq. (22) may be considered to modify the effective unbalance according to

\[ \frac{f_e}{m_R} \rightarrow \frac{f_e}{m_R} - (\omega_n^2 - \Omega^2 + 2i\tilde{\varphi}_n \Omega)w_B \]

\[ = \frac{f_e}{m_R} \left( 1 - \frac{m_R}{f_a} (\omega_n^2 - \Omega^2 + 2i\tilde{\varphi}_n \Omega)w_B \right) \]

(23)

The expression for the normal contact force becomes

\[ f_e = \frac{f_e}{(1 + i\mu)} \left( 1 - \frac{r_B}{r_E} e^{i(\psi + \phi)} \left( e^{i\omega} - \frac{c_e}{r_E} e^{i\phi} \right) \right) \]

(24)

The position of the contact orbit (C) occurs when \( \psi \) is such that

\[ \text{Im } f_e = \text{Im} \left\{ \frac{f_e}{(1 + i\mu)} \left( 1 - \frac{r_B}{r_E} e^{i(\psi + \phi)} \left( e^{i\omega} - \frac{c_e}{r_E} e^{i\phi} \right) \right) \right\} = 0 \]

(25)

If this cannot be met then a stable rub orbit is not possible. If it can be met then

\[ \text{Re } f_e = \text{Re} \left\{ \frac{f_e}{(1 + i\mu)} \left( 1 - \frac{r_B}{r_E} e^{i(\psi + \phi)} \left( e^{i\omega} - \frac{c_e}{r_E} e^{i\phi} \right) \right) \right\} > 0 \]

(26)

will indicate that a rub condition is possible. The requirement is therefore to impose a TDB whirl of appropriate amplitude.

![Figure 6](image-url)

Fig. 6 Plots of the real and imaginary parts of the complex contact force of Eq. (24). In (a), \( \psi = 54 \text{ deg} \) corresponds with the rub orbit C. In (b), \( \gamma = -4.5 \text{ deg}, r_B = 0.1 \text{ mm}, \) and \( \phi = 160 \text{ deg}, \) giving rise to \( \text{Im } f_e < 0. \)
Figure 6 shows example evaluations from Eq. (24). In Fig. 5(a) the TDB motion is zero \( r_b = 0 \) and it indicates that rub modes are possible at \( \psi = 54 \) and 132 deg. That for \( \psi = 54 \) deg corresponds to the original rub orbit C of Figs 2 and 5. When evaluated with imposed TDB synchronous forward whirl motion with \( \gamma = -4.5 \) deg, \( r_b = 0.1 \) mm, and \( \phi = 160 \) deg, \( \text{Im} f_c \) has no roots in \( \psi \) and hence a stable rub response is not possible, even though \( \text{Re} f_c > 0 \).

4. Simulations of the rotor being moved from contact orbit C back to contact-free orbit E

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. 7 shows a ramp-like change in applied synchronous AMB control force with 180 deg phase, causing loss of contact when it 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

Fig. 7 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.
apply the compensating AMB synchronous force with a precise knowledge of the phase. Figure 8 shows cases of ±150 deg with loss of contact at 340 N and 425 N, respectively. Figure 9 shows the contact force variation as the AMB force is applied for the case shown in Fig. 8(b).

4.2 TDB control to induce loss of contact

As an alternative to AMB control, movements of the rotor from the contact point C are possible through active displacement of the TDB, if actuation is available. Following the indicators from Fig. 6(b), Fig. 10 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 -4.5 deg. This causes the clockwise rotor movement in the synchronous frame that ultimately leads to loss of contact. This result shows the benefit gained from an understanding of the basic rotor dynamic

![Diagram](https://via.placeholder.com/150)

Fig. 10 Orbits due to a synchronous TDB displacement of amplitude 0.1 mm applied with -4.5 deg phase. The rotor recovers from the contact condition C to a contact-free state within the clearance circle.
response under contact conditions. Clearly, an idealized analytical model should not be the sole basis for control action, however, it may be used to ascertain the starting points for effective control to minimize contact durations.

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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