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Design of an active magnetic stabilizer of the dynamic behaviour of high speed rotors

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Abstract

A new concept of active dynamic stabilizer to operate the rotor at fairly high supercritical speed is here investigated. Instead of using the non rotating damping, as the classic literature suggest, a contra-rotating action is applied. Experiments performed on a flexible rotor being successfully stabilized by an eddy current magnetic damper are described. Advantages of contra-rotating the control forces of the active magnetic bearings of an electromechanical spindle are then discussed.

1 Introduction

High speed rotors are usually operated in the supercritical regime to assure a good self-centring condition [1]. The unbalance response and the reactions of bearings are reduced. Unfortunately, damping associated to the rotating parts of the rotor induces some dynamic instability, above a value of the angular velocity, being referred to as threshold of instability. Amplitude of the whirling motion exponentially grows up and may cause some dangerous failures to the rotor. To increase the threshold, designer applies to the stator a suitable amount of non rotating damping, being always stabilizing. Nevertheless, if the rotor is hung on active magnetic bearings (AMBs), the control current required to stabilize the whirling motion may be fairly large [2]. Sometimes there is no stator available to provide the non rotating damping. To overcome those limits an innovative use of magnetic damping was investigated. A rotating magnetic force is applied to the rotor by either an active or a passive device. This action provides a contra-rotating damping in the reference frame of the stator, since the rotor and the magnetic force rotate in two opposite directions. The dynamic stability threshold of the rotor can be increased up to a fairly high supercritical regime [3]. The so-called Jeffcott's rotor model can be used to introduce this concept [4]. If the complex coordinate $z = x+iy$ describes the rotor radial position, the equation of motion for a constant spin speed Ω is:

$$m\ddot{z} + \left(c_r + c_n\right)\dot{z} + \left(k - i\Omega c_r\right)z = m \cdot \varepsilon \cdot \Omega^2 e^{i\Omega t} \qquad (1)$$

where m is the rotor mass, c_r and c_n, the rotating and non rotating damping coefficients, k the stiffness and ε the rotor eccentricity. Rotating damping introduces a term proportional to the radial displacement z and to the angular speed Ω. Rotor runs above the critical speed, Ω_{cr}, to reach a good self-centring and strictly below the instability threshold, Ω_{th}:

$$\Omega_{cr} = \sqrt{\frac{k}{m}}\ ;\ \Omega_{th} = \Omega_{cr}\left(1 + \frac{c_n}{c_r}\right) \qquad (2)$$

Decreasing the rotating damping is often difficult, therefore a suitable non rotating contribution is usually provided. A contra-rotating action, c_d, can be used to contrast the rotating damping, c_r. It is applied in a reference frame rotating with angular speed Ω_d with respect to the stator, so as the equation of motion becomes:

$$m\ddot{z} + \left(c_r + c_n + c_d\right)\dot{z} + \left(k - i\Omega c_r - i\Omega_d c_d\right)z = m \cdot \varepsilon \cdot \Omega^2 e^{i\Omega t} \qquad (3)$$

If $\Omega_d = -\Omega$ and $c_r = c_d$, the instability threshold tends to infinity and all the forward and backward whirls are stable [5]. This condition can be found evenly if $\Omega_d c_d = -\Omega c_r$. Therefore the amount of stabilizing damping can be small if a suitable contra-rotational speed is set up. To apply this approach a contactless electromechanical coupling is used. A first possibility is resorting to the eddy currents induced by the rotor on a secondary contra-rotating and conductive disc or suitably modulating the current of an active magnetic bearing, to create a contra-rotating magnetic field.

2 Eddy current contra-rotating damper

The above described approach was tested on the prototype of flexible rotor depicted in Fig.1. A rigid frame holds up a pendulum rotor, being a disc hung to a quill steel shaft, while at the bottom a second disc rotor is located. Rotors are separately fed by two brushless motors. Optical sensors measure the radial displacements of the pendulum rotor. Non rotating damping is provided by the dissipation occurring in the supports, threaded joints and plates of the stator, while rotating contribution is associated to the rotor clamps, shaft and disc. Damping provided by the lower disc looks as non rotating, if it is fixed, either co-rotating or contra-rotating if it rotates along with the rotor or in the opposite direction. The upper disc is equipped with a permanent magnet, which induces some eddy currents in the conductive material of the lower disc.

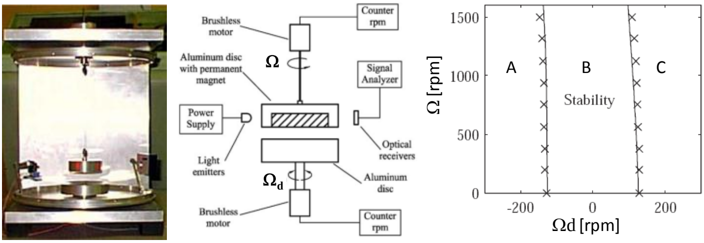

Figure 1: Test rig with the contra-rotating damper and experimental map of stability.

For a given gap between the two discs and when the two cylindrical whirling motions are analyzed, the first forward mode appears stable up to 1500 rpm, when the lower disc does not rotate. If the main rotor is kept rotating at 1500 rpm and a slow contra-rotation of the disc is applied and increased up to 230 rpm, the forward whirl is stabilized, but after a few seconds the backward mode is made unstable, against the statement of the literature that backward whirls are naturally stable [1]. An experimental map of stability was drawn (Fig.1). It shows that a contra-rotation faster than 125 rpm causes the instability of the backward whirl (A) while a co-rotation above 125 rpm makes unstable the forward whirl (C). Both are stable in (B). Therefore it was found that contra-rotation increases the dynamic stability of the rotor, provided that the instability of the backward whirl is prevented.

3 Contra-rotating damping in controlled rotors on magnetic suspension

The equation of motion of a rigid rotor suspended on AMBs, can be written as [6]:

$$\mathbf{M}\ddot{\mathbf{q}}+\left(\mathbf{C_n}+\mathbf{C_r}+\mathbf{C_d}+\Omega\mathbf{G}\right)\dot{\mathbf{q}}+\left(\mathbf{K}-\mathbf{K_u}-i\Omega\mathbf{C_r}-i\Omega_\mathbf{d}\mathbf{C_d}\right)\mathbf{q}=\Omega^2\mathbf{F_r} \qquad (5)$$

being **q** the four translational degrees of freedom monitored by the sensors, while the subscripts indicate non rotating, **n**, rotating, **r,** and contra-rotating, **d**. When the rotor is uniquely suspended on the AMBs and a PID control is applied, actions of bearings are non rotating and $\mathbf{C_r}$ and $\mathbf{C_d}$ vanish. The rotor is stable in the closed loop. If the control current is made contra-rotating, $\mathbf{C_n}$ is converted into $\mathbf{C_d}$. System is stable in absence of $\mathbf{C_r}$. If the internal dissipation is taken into account as $\mathbf{C_r}$= 70 Ns/m, the first forward whirl becomes unstable above 15200 rpm. This threshold can be increased if the control force is contra-rotated at 0.2Ω, but the backward whirl becomes unstable above 19000 rpm, being the limit of validity of the assumption of rigid body motion. In case of the severe rotating damping condition corresponding to $\mathbf{C_r}$= 700 Ns/m, the instability threshold decreases down to 3100 rpm. A contra-rotation at Ω with the 70% of the action provided by the AMBs when damping was non rotating allows having a higher threshold, at 4780 rpm, for both the forward and the backward whirling motions, respectively. A contra-rotation at 0.5 Ω with only one-half the non rotating damping provided at the beginning increases the threshold of the forward whirl to 3500 rpm, while the backward whirl remains stable. A larger benefit in reducing the current fed to the AMBs can be found if they are used just as stabilizing actuators on the rotor suspended on mechanical bearings.

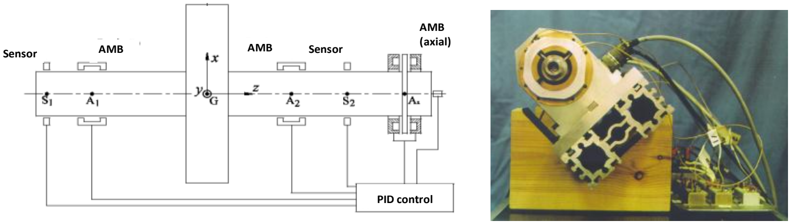

Figure 2: Test rig of a rigid rotor upon active magnetic bearings.

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