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Semi-active and active magnetic stabilization of supercritical rotor dynamics by contra-rotating damping

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ABSTRACT

High speed rotors are usually operated above the critical speed to achieve a good self-centring and to reduce the reactions of bearings. Damping associated to the rotating parts induces some dynamic instability, when the system rotates faster than an angular velocity defined as 'instability threshold'. To increase the range between the critical speed and the instability threshold the designer usually applies to the stator a suitable amount of non-rotating damping, being always stabilizing. In some application there is no stator available (spacecrafts, satellites) and in rotors suspended on active magnetic bearings the control current may be fairly large, if the dynamic stability has to be assured at a high spin speed. A new kind of active magnetic stabilisation is therefore proposed to overcome those limits. The damping action of the stator is here rotating, but its vector and the rotor spin speed are just opposite. Therefore that action appears as 'contra-rotating'. This approach provides an asymptotic dynamic stability of both the forward and backward whirling motions, even in the high supercritical regime. Design issues, implementation and results obtained in case of a semi-active system based on permanent magnets as well as of an active magnetic device are herein discussed.

1. Introduction

Above the angular speed known as 'instability threshold' a high speed rotor is prone to become unstable. This phenomenon is caused by the dissipation occurring within the rotating components of the rotor system and is associated to their intrinsic damping. This kind of damping is referred to as 'rotating' in the specialised literature [1]. When the dynamic instability occurs, the amplitude of some forward whirling motion suddenly grows up as an exponential function of time and the rotor system might be even destructed [1,2]. By converse the backward whirling motions are naturally stable, since their angular speed is just opposite to the spin speed of the rotor shaft. Dynamic instability is greatly dangerous, because its effects occur in correspondence of every value of the rotor spin speed greater than the threshold. Difference between the so-called 'critical speed' and the dynamic instability is evident. Critical speed corresponds to a natural frequency of the rotor system. Therefore at the critical speed the amplitude of whirling motion evenly increases, but the speed rate is smaller than in case of dynamic instability. This difference allows accelerating the rotor above the critical speed. It can reach a safe operating condition at a higher angular speed [3].

Daily practice shows that rotor system is usually operated above the critical speed, in the 'supercritical regime', to achieve a good self-centring. Nevertheless, the angular speed is always kept below the instability threshold. Unfortunately, very often the range between those two velocities is fairly small. Setting a suitable ratio between the rotor stiffness and inertia, respectively, to have a fairly low value of critical speed is a goal of the rotor design activity. In addition, a suitable amount of damping is applied to the stator to increase the instability threshold. It is known that the 'non-rotating' damping applied by the stator upon the rotor stabilizes the forward whirling motions, in both the subcritical and supercritical regimes. This action is expressively used to contrast the effect of the rotating damping, which makes unstable the forward whirls in supercritical regime, above the instability threshold.

Very often to assure a sufficiently wide range of angular velocity between the critical speed and the instability threshold, a fairly large amount of non-rotating damping is required. If the rotor is actively suspended upon active magnetic bearings this practice may require that a greater electric current is fed to the coils, up to some Amperes. In some special applications, like spacecrafts and satellites, there is no stator to apply the non-rotating damping, thus making the rotor potentially unstable even at a very low angular speed. Those technological limits motivated the research activity herein proposed.

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2. Research goals

A new approach to the dynamic stabilization of the high speed rotor is here investigated. The basic idea is resorting to a damping action whose versus in rotation is opposite to the rotor angular speed. This action looks as ‘contra-rotating’ in the fixed reference frame of the rotor shaft. This approach is meant to substitute the non-rotating damping provided by the stator. The benefit is that a fixed stator to assure the dynamic stabilization is no more required. Moreover, the amount of damping required for a given stable operation of the rotor is lower. To make possible this approach no contact between the stator and the rotor can occur. An electromechanical coupling is therefore suitable for this goal. Damping action can be either provided by the eddy currents induced by some permanent magnets on a fixed conductive element or by the electromagnetic forces generated by the actively controlled coils. Concept of expressively contra-rotating the damping was introduced in the literature in [4,5] where it was analytically demonstrated that the contra-rotation of damping increases the dynamic stability of whirling motions and their instability threshold. Moreover, modulating the control forces provided by the active magnetic suspension of the rotor was proposed and patented in [6]. Those two concepts followed some other cases of contra-rotation present in the literature, as the practice of counter-rotating the flywheel system equipping several spacecrafts to apply the attitude control through the gyroscopic effect, but without any specific correlation with the dynamic stability [7] or to the oscillations of large watercrafts as in [8]. Counter-rotating shafts appear in some industrial application, as in double contra-rotating wheels and shafts, where basically contra-rotation provides a suitable balancing of the forces applied to the bearings [9]. Additional examples are available in the field of engines for motor vehicles and concern the balancing optimisation [10]. In some recent contribution effect of damping in contra-rotating or slightly co-rotating elements was analysed as a potential source of instability [11].

In this paper two practical cases are described. A first device is based on the eddy currents induced by a permanent magnet applied to a flexible rotor disc on the surface of a contra-rotating disc fed by an electric motor. However a challenging issue of this application is analysing whether the implementation of this approach in case of the rotors actively suspended by radial magnetic bearings may provide additional advantages even in terms of reduction of the electric current fed to the system. It is known that Active Magnetic Bearings (AMBs) are applied to provide both the suspension and the balancing functions [12,13]. Magnitude of the electric current required by the control system to increase the stability threshold is often fairly large [14]. In this case some problems with temperature inside the bearing housing and with the magnetic field generated may arise [15]. Moreover, if any imperfection in the control implementation makes the active damping slightly rotating instead of non-rotating, a potential danger may be detected [16]. Overcoming those drawbacks of the AMBs may improve their effectiveness. It can be noticed that passive dampers [1,2], magneto-rheological devices [17] and some recent new solutions [18] do not completely stabilize the rotor when it rotates at very high speed.

3. Contra-rotating vs. rotating damping

To clarify the difference between the non-rotating and contra-rotating damping, respectively, the Jeffcott’s rotor model is preliminarily used as in several textbooks of rotor dynamics [1,2,19–22]. This model neglects the gyroscopic effect, since it describes only the whirling motion of the rotor centre in the plane x,y of a given cross section, in correspondence of the centre of gravity of the whole system. The complex radial coordinate $z = x + iy$ allows simplifying this analysis. In the fixed reference frame of the stator the equation of motion of the rotor centre is:

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

where the constant spin speed of the rotor is Ω, while ε is the static unbalance and m the mass. Damping coefficients are distinguished into rotating, c_r, and non-rotating, c_n, respectively. Stiffness, k, can be either associated to the supports or to the shaft or even to both [1]. It is worthy noticing that rotating damping adds a negative term to the stiffness in the fixed reference frame of the stator. This contribution is proportional to the radial displacement, z, and to the angular speed, Ω. This addition potentially makes unstable the whirl. Values of the critical speed, Ω_{cr}, and of the instability threshold, Ω_{th} can be computed as:

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

in accordance with [1,2]. To make highly supercritical the system a suitable ratio between k and m has to be set up. The instability threshold is increased by a favourable ratio between c_n and c_r. The operational speed, Ω_{op}, typical of the rotor service is chosen to be lower than the instability threshold, Ω_{th}, but always larger than the critical speed, Ω_{cr}.

This choice assures a good self-centring and reactions required to the bearings to contrast the effect of whirling motions become smaller. This is due to an alignment of the rotor centre of mass with the line axis. As Fig. 1 shows, at standstill the rotor centre of mass, P, is out of the geometric centre, C, by a quantity corresponding to the eccentricity, ε. A positive value of the amplitude of whirling motion, z_0, describes an increasing distance between the geometric centre, C, and the axis, as well as between the centre of mass, P and the rotor axis [2].

In condition of perfect self-centring, the radial displacement vector is rotated by an angle of 180° and point P is almost superposed to the origin of the reference frame, O. This result can be found by solving the equation of motion in case of static unbalance loading condition, to find the amplitude of the whirling motion:

$$\begin{aligned}
&C \to (x,y) \quad z = x + iy = x\cos(\Omega t) + y\sin(\Omega t)\\
&P \to (x_P, y_P) \quad (z+\varepsilon) = x\cos(\Omega t) + \varepsilon\cos(\Omega t) + y\sin(\Omega t) + \varepsilon\sin(\Omega t);\\
&\frac{z_0}{\varepsilon} = \frac{(\Omega_{op}/\Omega_{cr})^2}{\sqrt{\left[1-(\Omega_{op}/\Omega_{cr})^2\right]^2 + 4\left(\frac{c_n}{2\sqrt{km}}\right)^2 (\Omega_{op}/\Omega_{cr})^2}} \Rightarrow -1\\
&\text{when} \;\; z_0 \Rightarrow -\varepsilon\\
&P = [-\varepsilon\cos(\Omega t) + \varepsilon\cos(\Omega t)] + [-\varepsilon\sin(\Omega t) + \varepsilon\sin(\Omega t)] \Rightarrow 0 \;\; \text{and} \;\; P \Longleftrightarrow O
\end{aligned} \tag{3}$$

In this condition the rotor shaft rotates about its centre of mass, thus reducing significantly the actions exerted by the bearings.

Unfavourable effects of term $-i\Omega c_r z$ can be contrasted by the contra-rotating damping, c_d. This action rotates and its angular speed in the fixed reference frame of the stator is Ω_d. It is opposite to the rotor spin speed, Ω. Equation of motion becomes [4]:

$$m\ddot{z} + (c_r + c_n + c_d)\dot{z} + (k - i\Omega c_r - i\Omega_d c_d)z = m \cdot \varepsilon \cdot \Omega^2 e^{i\Omega t} \tag{4}$$

Critical speed is unchanged, while the instability threshold is modified. An equivalent viscous damping coefficient, c_d, is used to describe the contra-rotating damping and is assumed to be always positive. When the angular speed Ω_d is positive this action rotates along the same direction of the rotor speed Ω and is referred to as ‘co-rotating’. By converse, negative values indicate that Ω_d is opposed to Ω. In this case it is referred to as ‘counter-rotating’ or ‘contra-rotating’. If $\Omega_d = -\Omega$ and $c_r = c_d$, a sort of