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Active tilting-pad journal bearings supporting flexible rotors: Part I – The hybrid lubrication

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ABSTRACT

This is part I of a twofold paper series, of theoretical and experimental nature, presenting the design and implementation of model-based controllers meant for assisting the hybrid and developing the feedback-controlled lubrication regimes in active tilting-pad journal bearings (active TPJBs). In part I, the flexible rotor-active TPJB modelling is thoroughly covered by establishing the link between the mechanical and hydraulic systems for all regimes. The hybrid lubrication is herein covered in depth; from a control viewpoint, an integral controller to aid such a regime is designed using model-based standard tools. Results show slight improvement on the system dynamic performance by using the hybrid lubrication instead of the passive one. Further improvements are pursued with the active lubrication in part II.

1. Introduction

The fast development of the mechatronics has allowed a variety of machine elements to be upgraded. Among bearings, active magnetic [1,2], gas (compressible) [3–5] and oil-film (uncompressible) bearings [6,7] can be recognized. Within oil-film bearings, the development has focused on active tilting-pad journal bearings (active TPJBs) because it is an intrinsically stable bearing [8,9] so it can safely run under demanding operational conditions with or without the active feature. Under a mechatronic approach, sensing and actuating capabilities are incorporated into the active bearing design. Suitable actuators for TPJBs are of a hydraulic nature [10], although magnetic or piezo-electric [11,12] can also be implemented. In 1994, Santos [13] compared two types of hydraulic actuators for turning the conventional TPJBs into “active TPJBs”, the chamber and the oil radial injection systems, with the last one as the most appropriated choice [14]. By injecting high pressurized oil through orifices, commonly only one centrally machined at the pad surface, three lubrication regimes can be developed due to the combination of the hydrostatic with the hydrodynamic principles: the conventional (pure hydrodynamic), the hybrid (hydrodynamic plus hydrostatic) and the controllable (hydrodynamic plus variable hydrostatic). In Santos and Russo [15], the isothermal modelling of active TPJBs featuring the radial oil injection system was firstly introduced. Since then, a great amount of research has been carried out mainly in two fundamental branches. The first one involves the modelling of active TPJBs, and the second focuses on the control design for such bearings. When modelling the active TPJBs, all considerations of an elastotherhydrodynamic (ETHD) approach are maintained including also the radial oil injection, hydraulic and pipelines dynamics among the relevant effects. A detailed development of the modelling on active TPJBs can be found in [16–19]. On the other branch, the advances in the field of control design for active TPJBs have been deeply subjugated to the availability of accurate and reliable bearing models. Without such models to precisely predict the bearing properties, the integration of both areas for developing model-based controllers is limited. This limitation has circumscribed the control design to mainly classical PID controllers either via previous experimental system characterization or in-situ tuning. Theactual maturity of the active TPJBs modelling, which allows us to comprehend the physics behind it, can lead to designing model-based controllers at an early stage of the bearing design. This avoids calculating the PID parameters by heuristic means or by tuning them on site after the bearing is manufactured. Works related to control design for active TPJBs can be found in [20–26].

In the industry, the majority of the critical machines feature flexible rotors which make them worth analysing when supported by active TPJBs, in the same way as when they are supported by conventional TPJBs [27–32]. In rotating systems, the bearing dynamic properties heavily influence the whole system dynamics because they provide the main source of energy dissipation through the lubricating fluid film. Besides the damping reduction with the increased angular velocity, this property also reduces with the excitation frequency, which indeed

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lowers the damping ratio of the flexible system modes. In this case, the design of model-based controllers for governing the active TPJBs becomes even more relevant and challenging for increasing the damping of such modes, provided proper actuators are available. Only a few publications, such as [24,22,33], deal with the targeted systems from a theoretical and experimental perspective simultaneously. Contrarily, rigid rotor systems are more profusely covered [13,14,34,23,20,21].

In this framework, the main contribution of this work is fundamentally theoretical by presenting the modelling of flexible rotors when supported by active TPJBs. This modelling is based on the standard beam finite element formulation for the rotor and by including the full bearing matrices derived from an ETHD approach for the active TPJBs. This further includes the pad degrees-of-freedom (dofs) – tilt, bending and radial movement – and an extra dof – the servovalve spool-driven flow – which makes the link between the mechanical and hydraulic systems. Special emphasis is given to the modelling of the different lubrication regimes by analysing the influence of the fluid-film forces on the journal equilibrium and the bearing dynamic properties, leading to appropriated models for the passive, hybrid and active lubrication regimes. These models can be used for assisting the journal position changes under the hybrid lubrication regime or for designing model-based state-feedback controllers to develop the active lubrication, as presented next in part II. In this part, the hybrid lubrication is thoroughly covered and an integral controller derived using model-based tools is used to aid the journal equilibrium position changes. This study on flexible rotor-active bearing systems offers a more complete analysis that includes the flexible rotor dynamics and also serves to supplement the shortage identified previously.

2. The test rig facilities

The rotor-bearing test rig, shown in Fig. 1(a), resembles an industrial overhung centrifugal compressor. The driven torque is delivered through a flexible coupling connected to a layshaft, which is belt-driven by an AC motor. The rotor is supported by a ball and an active TPJB at the driven and free end respectively. Discs can be overhung at the shaft free end to resemble impellers and to increase the gyroscopic effect. None, one and up to two discs can be suspended. Without discs the rotor behaves as a rigid rotor at frequencies below 150 Hz, whereas any extra disc means analysing it as a flexible one. The system can be excited either through an electromagnetic shaker connected to the excitation bearing at the shaft end or through the active magnetic bearing placed between bearings. The main design and operational characteristics of the test rig are summarized in Table 1.

2.1. The active TPJB and lubrication regimes

The controllable bearing, schematized in Fig. 1(b), is a tilting-pad journal bearing with 4 bronze pads in a load-between-pads configuration. The pad is centrally pivoted with a rocker type pivot. The active or controllable feature of the bearing is rendered by an electronic radial oil injection system as proposed by Santos [15]. This injection system combines a hydrostatic with the hydrodynamic pressure distribution by injecting pressurized oil in the journal-pad clearance through, in this case, a single centred nozzle aligned with the pivot line.[1] The high pressure oil flow is injected by two high-frequency response servovalves, where each one couples to a pairwise of counter pads. Such pad sets are orthogonally installed. This servovalve-pad configuration enables us to freely exert controllable forces within the bearing plane so that any external force, such as imbalance, can be counteracted. One of the main components of the servovalve is the spool, whose position is driven by an input control signal which if set to positive, connects the supply port with one pad or if set to negative with the counter pad. With a zero input control signal, the servovalve's spool is centred to keep both ports closed, hence blocking the flow to the pads. However, due to tight fabrication tolerances between spool lands and ports being difficult to produce, the spool lands underlap the ports and a small leakage flow is always injected [39]. Further design parameters are presented in Table 2.

Fig. 2 depicts the layout of the hydraulic units connected to the active TPJB. This includes a flooding system for the conventional lubrication and the electronic radial oil injection system for developing the hybrid and active lubrication when enabled. These regimes, which are mathematically approached in the next section, can be further described as follows:

The Passive Lubrication Regime: provides the main bearing dynamic properties and its load carrying capacity due to the hydrodynamic lubrication. There is no controller implemented. It also acts as backup in case of failure of the radial oil injection system. This regime is utilized for benchmarking. *The Hybrid Lubrication Regime:* in this regime, which is one of the research objectives of this work, the high pressure unit is turned on and the hydrostatic contribution to the pressure build up is enabled. Depending on the servovalve's spool position, the high pressurized oil can be permanently injected by different pad combinations, leading to a change of the journal equilibrium position within the "x–y" plane and hence on the bearing dynamic properties. For horizontal machines, injecting from bottom pads has shown to produce a vertical bearing softening [40] and to reduce the system response amplitude [25]. In general terms, the higher the supply pressure the easier it is to change the journal equilibrium position. By using feedback signals, this regime can be aided by integral controllers to attain or maintain a predefined equilibrium, especially when servovalve dynamics are unequal [25].

The Active Lubrication Regime: if the control signals driving the servovalves are defined by a control law, then the hydrostatic fluid-film force exerted over the journal can be actively-controlled. This is achieved by using the system lateral movements or their estimates as feedback signals to synthesize classical or model-based control laws. This was carried out in [26] based on proportional-derivative controllers, which have been also used to demonstrate the bearing properties modification by control laws in ([17,19]). Provided a reliable rotor-bearing system model, system states can be estimated so that model-based state-feedback controllers can be designed and implemented.

3. The rotor - active TPJB modelling

The framework for the modelling of flexible rotor supported by active TPJBs when featuring the three lubrication regimes is set. Firstly, the generalized governing equations are obtained upon the linearisation of the equation of motion subjected to the fluid-film nonlinear forces. Then, the modelling of the active TPJB through the ETHD approach is briefly addressed. Full bearing dynamic coefficients, which includes the pads and hydraulic dynamics, are reviewed for the three regimes. Lastly, the coupling of the active TPJB properties with a beam-based finite element model of the rotor is covered. Table 3 summarizes the contribution of dofs from each subsystem, which will be used throughout this section. The rotor subsystem introduces 4 dofs per node, two translational and two rotational. The pads introduce three dofs per pad: the pad tilt, bending and radial translation (due to the pivot flexibility). Finally, two extra dofs are introduced because of the hydraulic system, one per servovalve.

3.1. Linking the rotor-bearing with the hydraulic dynamics for the different lubrication regimes

Fig. 3 presents the mechanical model of the integrated rotor-active

[1] Other configurations may also be developed, such as multi-orifice pads [16,35–37] or shifted nozzle pads [38].