Frequency-Dependent Adaptive Noise Cancellation-Based Tracking Controller

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Frequency-dependent adaptive noise cancellation-based tracking controller (ANC-TC) is a known technique for the stabilization of several nonlinear dynamical systems. This control strategy has been introduced and applied for the stabilization of a flexible rotor supported on full-lubricated journal bearings.

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1. Flexible Rotor with Lubricated Journal Bearings

In rotating machines, bearings are used to transfer radial and axial forces in a supporting structure ensuring a low value of the coefficient of friction and good system stability [1][2]. For cases with high loads and high rotational speeds, fluid film lubricated bearings are often preferred. The latter can be of two main categories: hydrodynamic bearings and hydrostatic bearings [3]. In the case of hydrodynamic bearings, the relative movement between the two coupled surfaces (journal and bearing) generates a pressurized fluid film that reduces the friction forces, ensuring the necessary support for the external load [3]. In the case of hydrostatic bearings, the pressure of the lubricating fluid is guaranteed by the action of an external pump, which injects pressurized lubricant into the bearing [4]. The most common version of hydrodynamic bearings is the full journal bearing, which consists of a rotor (journal) that rotates inside a bearing with a diameter slightly larger than that of the rotor, and the fluid film exists in the small space between the two (meatus) [3]. In the unsteady dynamical behavior, fluid film bearings can, however, present oscillating behavior (typical elliptical orbits) due to destabilizing cross coupling forces caused by the nonlinear fluid dynamic phenomena in the oil film [2][5]. To obtain acceptable operating conditions, it is necessary to simultaneously analyze the rotor-journal bearing couple in the case of a flexible rotor. These types of dynamic systems exhibit a particular type of self-excited vibration due to fluid dynamics phenomena in the oil film [2] known as *oil whirl* and *oil whip*, and are characterized by subsynchronous processional motions [6][7]. These vibrations appear when the subsynchronous vortex frequency reaches the natural frequency of the system [8] and is typically characterized by high vibration amplitudes. In recent years, research has shown that oil whirl phenomena are generated also when the journal bearing runs on micropolar lubricant [9][10][11]. Many scholars have studied the effect of lubricant contamination [12] and the nonlinear behavior of film-oil main bearings in rotating machines [13]. Furthermore, the performance of the bearing, in order to avoid instability phenomena, has been analyzed, studied and simulated considering factors such as misalignment [14], elasticity of the bearing liner [15], dynamic conditions and coupled surface roughness [16].

2. Active Noise Rejection Control

One of the objectives of recent research has been to propose control strategies for solving the classical problem of vibration rejection, in the frame of flexible mechanical structures [17][18], flexible rotor bearings control [19][20][21][22][23] and their active balancing [21]. The aim is to absorb, or reject, any vibrational phenomena on a rotating shaft connected to a motor, and stabilize it around an arbitrary equilibrium position [24], for example, using a closed-loop controller with notch filtering actions [24][25][26]. Good attenuation features are obtained if the disturbance frequency is well-known. Indeed, the stop bands of these filtering-based controllers exhibit very steep edges. Usually, in the presence of unmodelled dynamics, observer-based and sliding mode observer-based controls allow for the tracking control precision to be improved by adapting to the unmatched uncertainties [18]. Nevertheless, the use of an adaptive observer to solve this category of problems, the vibration suppression in flexible mechanical system, is not so widespread. For example [26], avoids the application of an adaptive observer due to the risk of control spillover. Conversely, the ANC control in D’Amato et al. [24] is implemented as an observer-based control. In [24], the equations of the elastic contributions in the journal bearings and the relative vibrations are modelled as a separated exosystem [27], which represents the disturbance acting on the control. Then, the ANC operation consists of the observation of such disturbance elastic contributions, so that the control injects, on purpose, a counterphase oscillation, aiming to delete them. This makes the closed-loop control independent of the operating conditions of the bearings: cavitated and uncavitated.

First results concerning controllability and observability problems in rotordynamic systems date back to the 1980s. The flexible rotor and the flexibly-mounted journal bearings were modelled by Stanway and Burrows, 1981 [22], as a spring-damping-mass system, with well-known natural vibration modes. They determined the system observability and controllability conditions in order to assign directly the closed-loop eigenvalues with a linear controller. A linear control approach was also addressed by Lei and Palazzolo, 2008 [25]. To this aim they used the Finite-Element-Method (FEM) to model the rotor dynamic system. In their approach, active magnetic bearings (AMB) were employed to handle the rotordynamic systems by acting coaxially to the inertial axis through a linear control law. In the framework of control techniques which uses AMB, Kumar and Tiwari, 2020 [28], investigated the rotordynamic system modeling unbalance and misalignment with the rigid body theory. The possibility of modeling the flexible system with a new set of nonlinear closed-form equations is a definite novelty introduced by D’Amato et al., 2022 [24], and retrieved in this presented study. By considering the lubricated bearing dynamic effects and with lubricant film cavitation conditions, an input–output feedback linearizing controller can be implemented. The proposed control law is adaptive with respect to the control and disturbance parameter (i.e., phase and frequency of the sinusoidal disturbance, corresponding to rotor angular speed of the rotor).

3. ANC with Frequency Estimation

A theoretical investigation of a novel ANC-frequency estimation (FE) technique designed to stabilize a flexible rotor shaft affected by self-generated sinusoidal disturbances. A work extends the adaptive noise cancellation tracking control (ANC-TC) algorithm presented by D’Amato et al. in 2022 [24][29], generalized to the case of unknown frequency. The disturbance frequency corresponds to the rotor operating angular speed (ω) [20][24][30], which is driven by an external actuator, so that uncertainties may arise in the frequency actual value due to actuation operating point fluctuations. Other incoming nonlinear phenomena, such as gyroscopic moments acting on the disk —for example due to asymmetries of the rotor support [31]-can make the operating frequency vary. The ANC-TC in [24][29] uses such a frequency value as a known parameter, which is also a parameter of the dynamics of the system. With respect to the specific uncavitated case study [29], a theoretical formulation has been provided in [24]: structural proofs for noise suppression estimation, cancellation and system stabilization are given when the disturbance frequency is known but not the initial condition.

The approach of [32] was convoluted in the hybrid logic (even if in a more general sense with respect to [33]). The general multi-harmonic disturbance case may be considered [17][32]. An I&I-based strategy, adaptive with respect to perturbation parameters, was recently presented and applied to a reversible cold strip rolling mill to control the speed and tension system [18], characterized by severe coupling effects, multiple state-variables, nonlinearities and model uncertainties. In [18], it was shown that the estimation errors follow an exponential convergence.

A recent research work [17] deals with the problem of active multi-harmonic disturbances cancellation in flexible mechanical structures, under the analysis of passivity properties of a closed-loop system. The controller operates an inner loop, which performs the position control of the system, while the frequency estimation is demanded to an outer control loop, elaborating the position measurements of the plant. A robust linear compensator scheme, non-accurate model-based, was employed and experimentally validated. An exponential cancellation of the disturbance was obtained.

The ANC-TC in [24][29] already showed an intrinsic robustness since the vibrational disturbances acting on the rotor were cancelled. Consequently, the introduction of a frequency identifier for vibrational modes improves the robustness of the method.

The closed-loop sinusoidal noise rejection is conceived in two phases: first, the operating frequency identification is performed as a combination of state-observer and asymptotical parameter estimation [32][33]; second, the asymptotical frequency estimate is fed back to the closed-loop adaptive noise cancellation control (ANC), which hooks the phase of the disturbance by injecting on rotor dynamics a counterphase sinusoid acceleration. The frequency estimation is in practice a warm-up phase of the overall closed-loop control [34][35]. This study proposed a unified theoretical structure including an I&I-based frequency estimator as a plug-in control block. The proposed control architecture design concerns the externalization of the FE process, which appears as an additive standalone block downstream to the ANC closed-loop, elaborating its output data and generating the asymptotical frequency estimate. Once such an asymptotical estimate converges at the steady-state closed-loop, the ANC control exponentially hooks the sinusoidal disturbance, following [24].

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