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Discussion on: "2-DOF Controller Design for Precise Positioning a Spindle Levitated with Active Magnetic Bearings"

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In the article authored by Arredondo and Jugo, a two-degree-of-freedom controller design is proposed to improve the positioning of the spindle in a particular electromechanical system consisting of a rotary flexible spindle hovered by active magnetic bearings. Their overall control design consists of a "stabilisation block", a "vibration minimisation block", and a "dynamics decoupler" block. To address the spindle positioning problem, they first separate the vibration from the hovering via decoupling, and then aim to ensure the spindle stability and vibration rejection via a two-degree-of-freedom controller formulation.

Intrinsic, and in fact an important first step, to the design of a sensible control method for systems of similar characteristics to that in the article by Arredondo and Jugo is the development of an accurate mathematical model of the underlying physical system. Such an accuracy in the mathematical model is vital in measuring the achievable performance of a controller and in converging on the choice of a suitable design algorithm. The flexible system in the aforementioned article has time-varying and nonlinear characteristics that cannot be captured solely by a single linear time-invariant model. There are modes that will have to be modelled using a parameter-dependent mathematical model, and uncertainties that will need to be adequately captured via highly directional parametric uncertainty. Nevertheless, the controller design in the article of our discussion utilises a linearised form of an approximated (order-reduced) model of the underlying complex system. In fact, this over simplification is obtained for a 'constant' rotational speed. The assumption of a linear model for systems supported on active magnetic bearings can be justified if the speed of rotor remains constant. If the speed of the rotor ranges over a spectrum of operations—even at a slow rate—the linear model assumption cannot be justified because the system matrix will be a function of the rotor speed and the system dynamics change considerably with the speed. Consequently, in such circumstances, due caution must be exercised and careful attention must be paid to the parameter-dependent nature of the plant instead of treating the speed-dependent changes in the dynamics as uncertainty. In fact, ensuring a desired level of performance may prove to be hard when the system operates over a range of speeds.

Another difficulty in the synthesis of controllers with sensible robust performance margins for systems of our discussion operating at different rotor speeds is the resonant nature of the flexible modes, which impose fundamental limitations on the achievable performance. In addition to this essential limitation, the parameter-varying nature of the plant and the demanding disturbance rejection specifications make specifically-formulated or trial-and-error designs for such complex systems inadequate.

Possible Advancements

To recap, physical plants with similar characteristics to that in the article of our discussion typically have intrinsic and involved features; namely, they are unstable, nonlinear, highly flexible with several flexible modes limiting

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the desired performance, and have a linear parameter varying dependency on the rotor speed, uncertainty on the natural frequencies of the flexible modes and inherit significant un-modelled substructure dynamics. One would also normally require stringent performance specifications in terms of stability (e.g., spindle), robustness to un-modelled dynamics and uncertain parameters, and disturbance rejection (e.g., vibration minimization) over an extended frequency range. Such complex dynamical features and strict performance requirements demand systematic, non-conservative, and advanced control methodologies.

Well-established control methodologies have been proposed to address the problem of interest; for example, for an application of the $\mathscr{H}_\infty$ loop shaping method see [3, 4], or [8] for an application of the μ synthesis design method, or [7] for an application of the gain scheduled $\mathscr{H}_\infty$ control design, or [13, 10, 9] for related contributions. In fact, a combined application of $\mathscr{H}_\infty$ loop shaping and μ-synthesis to design robust controllers for systems supported on active magnetic bearings is developed in [5]. A combination of parametric (structured) and unstructured uncertainty (i.e., coprime uncertainty) is used in [5] to model the physical plant, and the design allows one to directly incorporate performance requirements in terms of the plant loop shape and achieve guaranteed bounds on the performance degradation. The technique of [5] enables the incorporation of a parameter-variation (due to the rotor speed) into the nominal plant (as opposed to treating it totally as unknown uncertainty), leading naturally to a gain-scheduled or parameter-dependent implementation of the synthesized robust controllers.

It would be of interest if one considers modelling the system of interest in the aforementioned article via a parameter-dependent nominal linear model, which would allow one to explicitly capture the changes of the dynamics due to the change or the rotor speed instead of treating them solely as unmodeled dynamics. Furthermore, the uncertainty in the rotor natural frequencies can be captured by parametric uncertainty. Note that the generic unmodeled dynamics can be captured via unstructured coprime factor uncertainty.

Another intriguing advancement would be to combine the two-degree-of-freedom formation and $\mathscr{H}_\infty$ loop shaping control design paradigm, similar to that in [2], which provides assurance and reliability that the controller obtained meets the pre-specified performance specifications and ensures a sensible robust stability margin. Utilising the two-degree-of-freedom approach in [2] the design of controllers for achieving the desired stability requirements and disturbance rejection specifications are not separated, dissimilar to [6], for example. Note that these methods provide simple tools for indicating how good a design is in achieving the desired robustness and performance objectives.

An advanced version of the aforementioned article in a follow-up publication could aim to include a succinct literature review leading to a different motivation, in light of the discussion in the preceding paragraphs and the recent developments [1, 11, 12], for the considered positioning problem in the proposed framework. An extended discussion on the prospectives and consequences of proposed two-degree-of-freedom controller formulation in a broader framework could also enable potential advancements and possibly generalise its application to a broader class of problems.

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