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The Effects of Interval Uncertainties and Dynamic Analysis of Rotating Systems with Uncertainty

S. Sindhu[1*]

[1*]*Research Analyst, Centivens Institute of Innovative Research, Coimbatore, Tamil Nadu, India.*

E-mail: sindhuanbuselvaneniya@gmail.com, https://orcid.org/0009-0007-0956-8523

Abstract--- The idea of dynamical systems has been driving the technological explosion since the turn of the 20th century. Scientific and engineering disciplines have greatly advanced as a result of dynamical systems research studies. As a result, numerous significant and intriguing findings regarding the stability and stabilization of dynamical systems have been reported by research communities. System uncertainties, time delay, external disturbances, and system nonlinearities are some of the major elements that impact the dynamical system's stability. It should be mentioned that providing an exact mathematical model representation is not always feasible when simulating real-world systems. The mathematical model and the real-world systems might differ or contain some errors. System uncertainties are a common term used to describe these errors. A set of mathematical equations that describe a real-world system with some known errors are then modified to produce the desired result. A controller design may be used exclusively, depending on the known factors and the complexity or simplicity of a control system problem. Actuator failures are one of the most crucial parts of a control system since they can impair the system's functionality. Actually, the assumption that the actuators are either normal or in good condition forms the basis of the majority of intriguing studies. As a result, designing a controller for dynamical control systems that maintains the closed-loop system's performance and stability even when all of its control components are in good working order is a major task.

Keywords--- Electric Motor, Electro-mechanical Energy, Sensor, Self-monitoring.

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I. Introduction

An electro-mechanical energy conversion device that transforms electrical energy into mechanical energy (output displacement) is an electric motor. Generally, there are two types of electric motors, viz., DC motors and AC motors. While AC motors can be divided into synchronous/asynchronous and induction motors, DC motors can be divided into shunt and series motors. The induction motor is regarded in the work as the plant and the primary instrument that the research is conducted on (Zuo & Wang, 2017). The most popular electrical motor for a variety of industrial applications is the three-phase induction motor. Due to its straightforward and durable design, low cost, good operating characteristics, lack of a commutator, and good speed regulation, three phase induction motors supply nearly 80% of the mechanical power used by industries. The three-phase induction motor uses the induction concept to transfer power from the stator to the rotor winding. Because it operates at a speed different from the synchronous speed, the induction motor is also known as a synchronous motor (Lara-Molina et al., 2019). Due to wear and tear, the various components of the IMs—stator, rotor, slip rings, frame, core, brushes, rotor bars, coils, terminal box, fan blades, laminations, magnets, drives, loads, outer casing, bearings, windings, shafts, couplings, foundation bolts, gear boxes, etc.—that make up the mechanical and electrical parts may malfunction or fail as a result of the motor's continuous operation. Despite being dependable, strong, and nearly indestructible, IM can experience a variety of malfunctions for a variety of reasons, including overvoltage, short circuits, aging, vibrations, temperature increases, friction, and more (Zhao et al., 2022). Unbalanced stator currents and voltages, rotor malfunctions, torque oscillations, torque reduction, overheating, and excessive vibration are some of the consequences of such issues in induction motors. Additionally, as the rotor rotates continuously, friction causes the bearings to wear out, which leads to bearing faults and damage from the frictional effect. The eccentricity changes, the air gap becomes uneven, the shaft tilts, and the rotation becomes uneven. Additionally, these motor malfunctions can cause higher order harmonics to occur, damage to the windings, and an increase in the magnitude of specific harmonic components of currents and voltages. Lastly, the following kinds of faults, which can be divided into three categories, will impact the performance of the induction motor (Cavalini et al., 2017).

The organization structure of the work as follows: The structure model in section 1, The relevant introduction of the different soft computing techniques that were used for the condition monitoring of the dynamic machines in section 2. The system is meticulously modeled using hydrodynamic theory and finite element analysis. in section 3, Design and evaluation of a controller is presented in section 4; and finally in section 5, presents conclusion of this work (Sahu et al., 2022).

II. Literature Review

A small introduction of the different soft computing techniques that were used for the condition monitoring of the dynamic machines (the motor current signature analysis) is being presented with respect to the fault detection and analysis point of view (De Castro et al., 2017). The work carried out in this thesis is related to the detection and analysis of faults using Fast Fourier Transform (FFT), Short Term Fourier Transform (STFT), Gabor Transform (GT), Wavelet Transform (WT) and the Park's Vector Representation (PVT). This is followed by the classification of the extracted features using machine learning and data mining techniques such as J48 Decision Tree algorithm, Random Forest Tree algorithm. Once, the faulty signal is being detected by the particular sensor, the next step after fault identification is the fault analysis using different types of DSP techniques and finally rectifying fault, thus protecting the dynamics machines from further damage (Fu et al., 2023). Digital technology advancements are necessary for signal-based diagnosis. The SP schemes search quantities sampled from the actual machine for known fault signals. Appropriate signal processors then keep an eye on the signals. In order to separate the fault from other phenomena and reduce sensitivity to operating conditions, signal processing can be used to improve the signal to noise ratio (SNR) and normalize data (Dourado et al., 2018). Understanding the model and machine parameters is not necessary for data-based diagnosis. It only uses clustering techniques and signal processing (Ramos et al., 2019). Techniques for signal processing can be further subdivided into various groups. Here, the subclasses are displayed and discussed separately (Chudasama, 2016). The different DSP schemes that are used for the fault analysis in the research work are mentioned in the previous section.

III. Methodology

For this study, a double-disc rotor system with oil-film bearing support is taken into consideration, as shown in Figure 1. This section describes the system's modeling in detail using hydrodynamic theory and finite element analysis. Additionally, the established dynamic model's modal property and response solution are presented, providing the deterministic foundation for the ensuing interval uncertainty analysis.

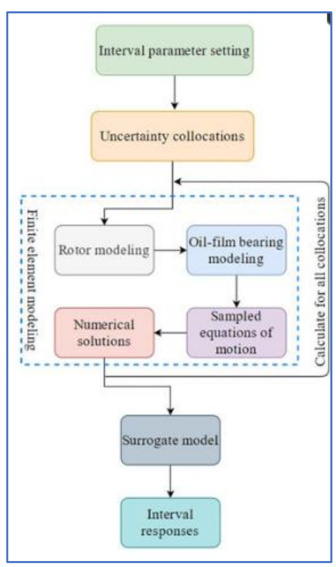

Figure 1: Proposed Block-diagrammatic Approach

The study of physical systems governed by a consistent set of laws over time that are represented by difference and differential equations is known as dynamical systems. A dynamical system is made up of a dynamical rule that specifies the immediate future of all state variables and an abstract phase space, also known as a state space, whose coordinates describe the state at any given time. Dynamical systems theory has garnered a lot of attention in recent decades due to the discovery of chaos and strange attractors, and it has been discovered to have tentacular connections with numerous branches of mathematics. The motion of planets in solar systems, the spread of diseases in a population, the growth and form of plants, the interaction of optical pulses, or the mechanisms governing electronic circuits and heartbeats are just a few examples of the amazing variety of behavior that dynamical systems can simulate (Farmer, 2021). There has been remarkable development in the research of dynamical systems because of its wide range of applications in the fields such as aerospace, defense, robotics, telecommunications, biological systems and signal processing. Moreover, it has been recognized that the practical applications greatly depend on the qualitative behaviors of dynamical systems. In particular, stability analysis issue is one of the main properties of the dynamical system, which plays a crucial feature in the design of practical systems. Therefore, in general it is important, both theoretically and practically to investigate the stability of the dynamical systems. When modeling practical systems, uncertainties are inevitable due to the modeling errors and external forces, which will affect the performance of the system. Rotor System Model Supported by Oil-film Bearings shown in Figure 2.

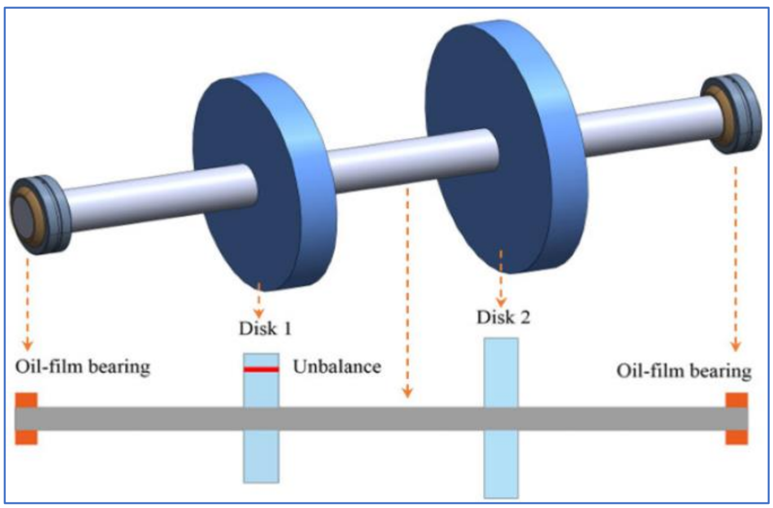

Figure 2: Rotor System Model Supported by Oil-film Bearings

A convex constraint on an unknown variable is specified by LMI. To solve a convex optimization problem with LMI constraints or to ascertain whether an LMI is feasible (for example, whether a vector y exists such that LMI(y) = 0), effective numerical techniques are available. LMIs can be used to formulate a variety of optimization problems in signal processing, control theory, and system identification. LMI techniques have become a potent design tool in a variety of fields, including structural design, system identification, and control engineering.

For the proper functioning of a dynamical control system, the most important property is stability. A dynamical system is stable if the system output remains bounded for all inputs which are bounded. Such a stability is otherwise called as Bounded-Input Bounded-Output stability for linear time invariant systems. Furthermore, the tools for studying stability may vary for each dynamical system depending upon whether the dynamical system is nonlinear, linear, discrete, continuous, discontinuous, stochastic, deterministic, etc. Therefore, a control protocol has to be designed such that the dynamical system is steered to an equilibrium with the desired output. This is problem in dynamical systems is termed as stabilization problem. The problems concerned with stability analysis has developed into a major research aspect in the field of dynamical control systems. In order to deal with the large number of stability and stabilization issues of various kinds of dynamical control systems, numerous control design protocols have been rigorously developed Finite-time stability problem has been researched well because of its high potential in theoretical and practical applications. Unlike the asymptotic stability, which speculates a given dynamical system in an infinite time interval, finite-time stability speculates a given dynamical system in a finite-time interval. Considerable number of researches on finite-time boundedness, finite-time stability and finite-time stabilization as in have been discussed by using Lyapunov stability approach together with LMI technique for various dynamical control systems.

IV. Experiments and Results

Both deterministic and indeterministic aspects of the rotor-bearing system shown in Figure 1 are examined. Figure 3 shows the rotating system's Campbell diagram based on the simulations. The findings indicate that there are two forward synchronous critical speeds—556 rpm and 2234 rpm—in the speed range of interest. Figure 4 displays the rotating system's first two order mode shapes, which match the critical speeds' natural frequencies. These deterministic features aid readers in comprehending the intrinsic qualities of the rotating system being examined and offer direction for uncertainty analysis.

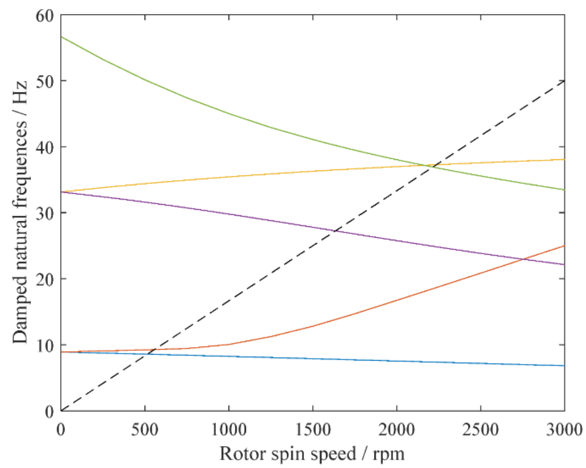

Figure 3: The System's Campbell Diagram

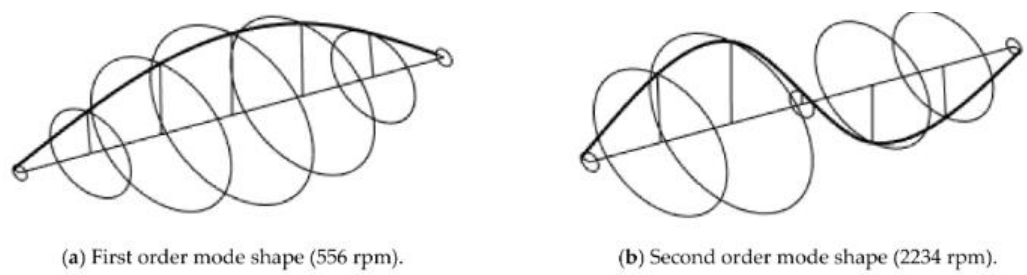

Figure 4: The System's Mode Shapes at Critical Speeds

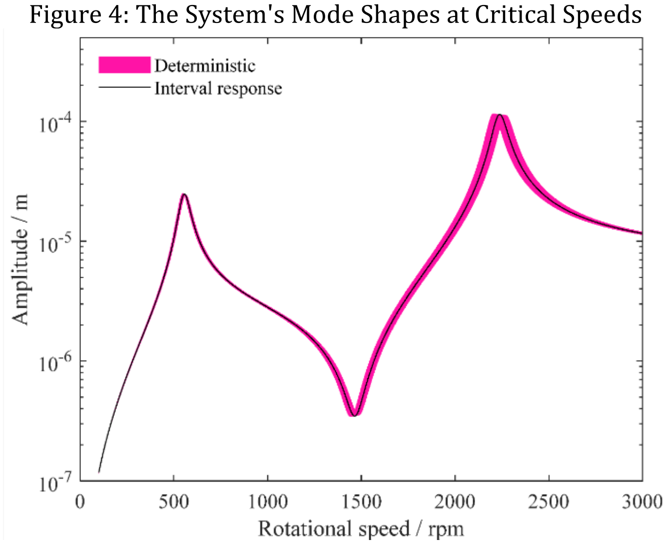

Figure 5: The Steady State Response of the System Under Interval Elastic Modulus

Shaft stiffness, which is frequently represented in the elastic modulus, is the first interval variable taken into account. The simulation is run with a 3% interval coefficient, and the steady state response, time history, and shaft orbit are among the interval results displayed in Figures 5 and 6. It is demonstrated that the interval elastic modulus has an overall effect on the speed scope under study, with the exception that deviations are negligible at relatively low rotation speeds. Furthermore, the responses—particularly the second mode—are more impacted after the first critical speed. One unique characteristic of the interval frequency response is that, despite the expansion of the resonant region brought on by the frequency deviations, the amplitude deviation around the second critical speed is minimal. Indeed, the natural properties of the rotating system are significantly impacted by the elastic modulus.

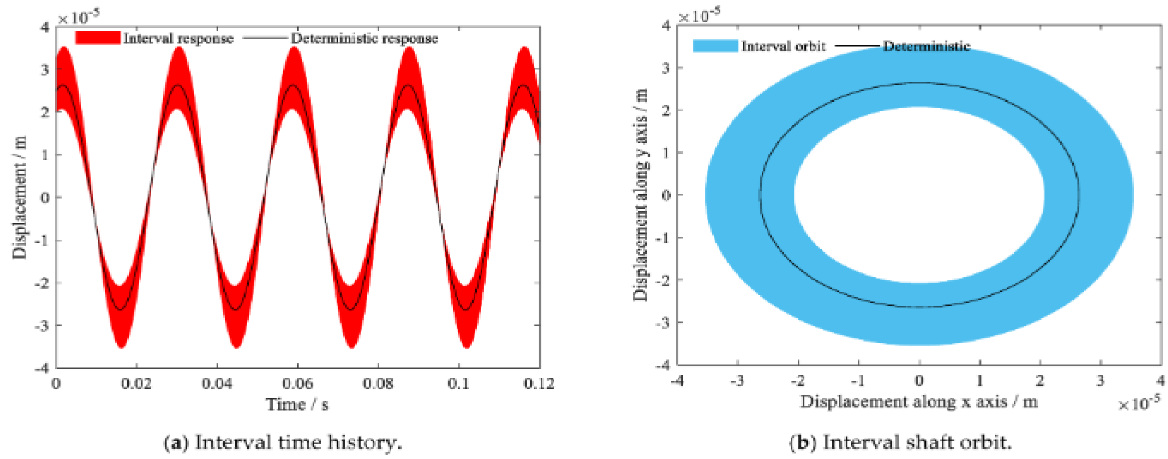

Figure 6: System Orbit and Time History Under Interval Elastic Modulus

The main findings of this thesis include the derivation of sufficient conditions for the addressed control system in the form of LMIs and the solution of stabilization problems for various dynamical system types using Lyapunov functionals and some recently developed inequalities. Lastly, numerical examples are used to validate the theoretical results that have been rigorously established.

V. Conclusions

The research work in this thesis, has focused primarily on the stabilization of various kinds of dynamical systems when subject to uncertainties. By utilizing Lyapunov stability theory, the stabilization of switched time-delay systems, fuzzy time-delay systems, stochastic interval time-delay systems, fractional order systems and biological economic systems have been investigated. More specifically, by using a state feedback controller the sufficient conditions for stability and stabilization of these considered dynamical systems when subject to the effects of certain parameters such as nonlinearities, actuator faults which may be linear or nonlinear, input saturation which may be symmetrical or asymmetrical and environmental disturbances have been recorded. Moreover, to establish the stability and stabilization of these dynamical control systems reliable control strategy, equivalent input disturbance-based tracking control strategy, passivity-based control strategy, finite-time control strategy and resilient control strategy have been employed. Without any exception, the controller protocols designed in each chapter of this thesis have been obtained as LMIs and have straightforwardly obtained the controller gain matrices by utilizing MATLAB LMI toolbox. Additionally, to validate the obtained theoretical LMIs, numerical examples with their corresponding graphical results have been lined up in each chapter to highlight the validity of the accomplished results.

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