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Computational Framework using Bond Graph and FEM to Model the Squeeze Film Damper Supported on Rotors

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Abstract—*The squeeze film damper (SFD) is essential for improving the rigidity of spinning machinery and reducing vibrations. Finite Element Method (FEM)and the Bond Graph modelling were used to provide a computational framework for accurately simulating an attached rotor with a squeeze film damper. This article provides a summary of the method used to create an analytical structure that integrates Bond Graphs' energy flow modelling features with the structural dynamics captured by FEM. The methods used to simulate squeeze film dampers in supported rotor systems utilizing FEM and the bond graph approach are discussed in this paper, which emphasizes the usefulness of the computational framework built for comprehending and improving squeeze film damper performance. The framework is used in a variety of rotating machinery systems for vibration analysis, stability evaluation, and squeeze film damper design parameter optimization.*

Keywords: *Squeeze film damper (SFD); computational framework; Finite Element Method (FEM); Bond Graph; vibration control;*

INTRODUCTION

Squeeze film dampers (SFDs) have been effectively employed to increase damping, expand the range of rotating speed, and decrease vibration levels in numerous applications, including aircraft jet engines, turbo machinery, and commercial compressors. The improvement in operating speed and power-to-weight ratio in turbo-machinery design has led to a lighter and more efficient system of flexible rotor bearings. A detailed diagram of the squeeze film damper is shown in Figure 1.

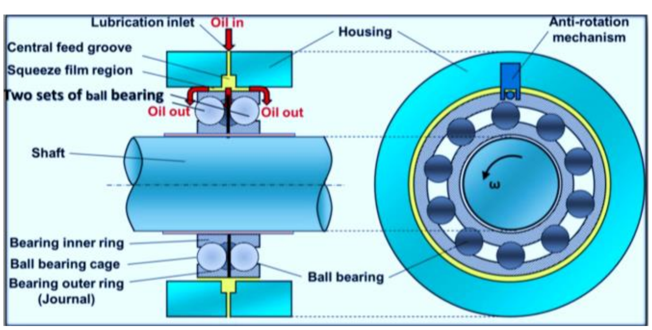


Figure 1: Detail view of squeeze film damper with two sets of ball bearing

SFDs are frequently used in high-speed turbomachinery because of their capacity to lessen the forces transmitted to the structure and minimize the amplitude of rotor vibrations. Finding a practical way to reduce machine vibration is essential since rotor vibration is an increasingly common issue. Internal and external excitation is the most common rotor excitation sources. A few examples of internal excitations are imbalance, misalignment, friction, and other elements. Thermal creep, for example, as well as fluid shock are examples of external excitations. Resonance will occur if the stimulation frequency is close to the natural frequency. In addition to reducing the rotor's lifespan, this will increase the likelihood of mishaps and cost you money [1, 2]. The extremely nonlinear behavior of squeeze film dampers, which is influenced by the rotor's movement and has a direct bearing on the dynamics of the rotor in the system, is evident. Generally speaking, adding SFDs to rotors significantly improves the system's vibration characteristics; nevertheless, due to their nonlinear properties [3–5]. In order to assure the correct design and performance of SFDs, a rotor dynamic model must be constructed in order to analyze the damping efficacy of SFDs on the vibration characteristics of high-speed turbomachinery. The operating speed, rotor imbalance magnitude and dampening, and damper design parameters are typically linked to the satisfactory performance of SFDs [6]. By tangentially raising and radially lowering the fluid film response forces, the fluid inertia effect increases the damping capacity of SFDs. In various research, both theoretically and physically, It has been explored how lubricant inertia affects SFD damping capacity. [7–9]. Theoretically, the mass distribution at the mid-span and supports of a simple flexible rotor model with SFDs, centering elements, and has been investigated[10]. In order to determine how design and operational parameters affect Direct numerical integration was used to investigate the bifurcation onset speed and nonsynchronous behavior spectrum in the steady-state response of a basic flexible rotor with and without retaining springs. The equation of movements created using the straightforward flexible rotor model is unsuitable for the majority of rotodynamic applications, which demand an accurate calculation of rotor displacements. Multi-mass flexible rotor models, on the other hand, accurately portray rotor behavior. The multi mass rotor model divides the continuous rotor into a finite number of components with a finite number of degrees of freedom. Many theoretical investigations on multi-mass, multi-degrees-of-freedom rotors using SFDs have been done. [11, 12]. The constant and transient reactions of a Jeffcott rotor supported by SFD with retainer springs were studied while fluid-film cavitation was taken into account. The results show that the static eccentricity ratio of the journal should be less than 0.4 to produce a low transmission force [13]. [14] investigated journal static eccentricity under short bearing and cavitated-film approximations, as well as steady responses via Poincare map, whirl orbit, bifurcation diagram, and power spectrum analysis. In this paper, we present a detailed development process of a computational framework for modeling the behavior of a squeeze film damper supported on a rotor using the Finite Element Method (FEM) and Bond Graph modeling techniques. We want to give a thorough knowledge of the dynamic behavior and energy transfer inside the squeeze film damper system by merging these potent approaches. The FEM-based supported rotor mathematical modeling and the bond graph modeling of the squeezing film damper are covered in detail in the following sections. We highlight the significance of effectively modeling the fluid flow, resistive, and capacitive aspects in the bond graph model, including crucial elements such fluid viscosity, clearance, and pressure distribution. We create an interface that makes data sharing and coupling easier while assuring correctness and consistency in the computational framework to enable seamless integration between the Bond Graph and FEM models. To achieve convergence between the two models, an iterative solution approach is used, improving the precision and dependability of our simulations. To show how successful the computational framework is, validation and analysis are done. We intend to test the correctness of the established computational framework in predicting vibration characteristics and improving damper parameters by comparing the simulation results with experimental data or analytical solutions. In order to emphasize the practical use of the computational framework in various rotor designs and operating situations, the study finishes by giving case studies and findings. We also explain the ramifications of our results, highlighting the potential for squeezing film dampers with optimal designs to enhance the performance and dependability of rotating equipment systems. This study intends to expand our knowledge of squeeze film damper behaviour in supported rotor systems and help us optimize it. The created computational framework has the potential to have a substantial influence on a number of industrial applications, improving the stability and control of vibration in rotating machinery and opening up new directions for future study and innovation in this important area.

2. PRINCIPLES OF SQUEEZE FILM DAMPERS:

- Fluid film circulation and hydrodynamic motion are the underlying concepts of squeeze film dampers. These dampers play an important role in increasing the stability and dependability of rotating equipment systems by effectively dispersing energy and lowering vibration amplitudes. For planning, creating, and utilizing squeeze film dampers in a range of industrial applications, it is crucial to comprehend the fundamental principles.
- The following is the hydrodynamic action principle: According to the hydrodynamic action concept, squeeze film dampers (SFDs) create a thin fluid film between the rotor and the damper as a result of their relative motion. By applying hydrodynamic forces, this fluid layer functions as a damping medium, preventing relative motion and attenuating vibrations.
- Formation of a Fluid Film: The fluid between the surfaces is squeezed as the rotor rotates, increasing pressure. The hydrodynamic forces created by this pressure counteract the relative motion and reduce system vibrations.
- Influence of Fluid Film Thickness: The SFD's damping characteristics are significantly affected by the fluid film's thickness. A thin coating provides for greater damping effects, but it also increases the danger of direct contact between the rotor and the damper, which can cause unwanted friction and wear.
- Fluid qualities: The qualities of the fluid utilized have a considerable impact on the damping performance of the SFD. Higher viscosity fluids provide more damping and hence better vibration reduction. The, on the other hand,Role of Surface Roughness: The surface roughness of the rotor and damper plays a vital role in the formation and maintenance of the fluid film. Proper surface finishes are essential to ensure optimal hydrodynamic action and effective damping.
- Damping Effect and Energy Dissipation: The squeeze film damper's principal function is to dissipate energy and lower vibration amplitudes. The amplitude of vibrations diminishes as the fluid layer absorbs energy from the vibrating system, resulting in greater stability.
- Design Optimization: To obtain the intended damping performance, characteristics such as film thickness, fluid properties, and surface roughness must be carefully considered throughout the damper's design process. To balance damping efficiency with the danger of direct contact, optimization approaches are used.
- Computational Modeling: Accurate computational models require an understanding of the concepts underpinning SFDs. To forecast the damper's behavior under different operating situations and help in the optimization process, mathematical formulae and numerical simulations are utilized. Industrial Applications: Squeeze film dampers find extensive use in various rotating machinery applications, such as gas turbines, aircraft engines, and high-speed rotating equipment. Their ability to enhance

stability and reduce vibrations makes them a critical component in ensuring reliable and efficient operation.
- Ongoing Research: Owing to their significance in rotating machinery, ongoing research focuses on improving the understanding of squeeze film damper principles and developing advanced modeling techniques. The continued exploration of new materials and design configurations further enhances their performance in real-world applications.

The flow of a thin film of fluid between the rotor and the damper creates hydrodynamic forces that reduce vibrations through the use of fluid dynamics in squeeze film dampers. The Reynolds equation, which controls the pressure distribution in the fluid film, may be used to explain the fluid dynamics inside the damper. The Reynolds equation for a squeeze film damper can be given as:

$$\frac{\partial h}{\partial t}+U\frac{\partial h}{\partial x}+V\frac{\partial h}{\partial y} = \frac{h3}{R}\left(\frac{\partial P}{\partial x}\frac{\partial h}{\partial x}+\frac{\partial P}{\partial y}\frac{\partial h}{\partial y}\right)+\frac{6\mu}{R}\frac{\partial}{\partial x}\left(h\frac{\partial V}{\partial x}\right)+\frac{6\mu}{R}\frac{\partial}{\partial y}\left(h\frac{\partial V}{\partial y}\right)$$

where:

- t is time is the fluid film thickness.
- P is the pressure within the fluid film.
- μ is the dynamic viscosity of the fluid and V are the velocity components in the x and y direction.
- R is a characteristic length or the radius of the damper.
- (x, y) are the velocity components in the x and y direction, respectively.

The fluid layer's internal pressure dispersion affects the damper's dampening and load-carrying capacities. A non-uniform pressure distribution results from the fluid layer being squeezed as the rotor turns. The hydrodynamic forces produced by this pressure distribution counteract the relative motion and reduce system vibrations.

The viscous shear within the fluid sheet causes mechanisms for energy dissipation within the damper. A relative velocity gradient that exists when the fluid moves between the rotor and damper causes viscous energy dissipation. This lost energy is mostly transformed into heat, which lowers the vibration amplitudes and boosts system stability.

FINITE ELEMENT METHOD (FEM) FOR SUPPORTED ROTOR MODELLING OF SFD.

The partial differential equations that explain how physical systems behave are solved numerically using the finite element method (FEM). The following procedures for modelling will be used when using the FEM to analyse the dynamic behaviour of rotating structures under different loads and boundary conditions in the context of rotor dynamics [16]

I. I. Discretization: To describe the rotor system's shape and physical characteristics, the FEM discretizes it into smaller pieces, such as beams or shells. Each element may be approximated by the behaviour of the system since it is defined by a collection of nodes and their corresponding shape functions.

II. Formulation of Governing Equations: The dynamic equations of motion for the rotor system are derived based on the principles of mechanics, considering factors such as mass, inertia, and external forces. These equations are expressed in matrix form, incorporating stiffness, mass, and damping matrices.

III. Element Matrices: Each element in the rotor system is coupled with matrices that indicate its stiffness, mass, and damping qualities. These matrices are formed from the geometry of the element, material characteristics, and the specific governing equations utilized.

IV. The element matrices are combined to create global stiffness, mass, and damping matrices, which represent the overall performance of the rotor system. To complete this assembly, the nodes of close components must be joined, and adequate boundary restrictions must be provided.

V. Problem with Eigenvalues The eigenvalue problem must be resolved by figuring out the system's innate frequencies and mode shapes, which is how the dynamic behavior of the rotor system is characterized. Iterative solutions are used to the eigenvalue issue.

VI. The FEM may be used to study the dynamic response of the rotor system under various operating situations after the natural frequencies and mode shapes have been established. To model the transient response of the system, time integration techniques like the Runge-Kutta method or the Newmark method can be used.

VII. VII. Validation and Optimization: Comparing FEM results to experimental data or analytical solutions might help to validate the findings. To improve the model's accuracy, discrepancies can be further investigated. The FEM may also be used to optimize designs, which entails changing features like shape, material properties, or damping coefficients to satisfy desired performance criteria.

VIII. VIII. By utilizing FEM in rotor dynamics, engineers may gain a thorough understanding of the dynamic behavior of spinning structures. It allows for the examination of critical variables under various operating conditions, such as natural frequencies, mode shapes, and dynamic responsiveness. The FEM is a helpful tool for rotor system performance and design optimization across a range of industrial applications because of its capacity to handle complicated geometries, material heterogeneity, and boundary conditions.

4. SQUEEZE FILM MODELLING:

The mathematical description and study of the fluid dynamics, pressure distribution, and energy dissipation processes within a squeeze film damper (SFD) is known as squeeze film modelling. The goal is to comprehend and foresee the behaviour of the fluid film that develops between the spinning shaft and the inner surfaces of the damper. In order to reduce vibrations and improve stability in spinning machinery, the damper's performance must be optimized.

- First, fluid dynamics: Equation of Reynolds: The Reynolds equation is the main mathematical formula guiding fluid flow in the squeezing film. It takes into consideration the fluctuation in fluid pressure brought on by the forces of viscosity operating in the little space between the rotor and the inner surface of the damper.
- To more precisely examine the fluid flow characteristics in the damper, the complete Navier-Stokes equations may occasionally be solved. This method is usually employed for particular types of study; however, it might be computationally demanding.

I. Pressure Distribution:

- Hydrodynamic Pressure: The relative motion between the surfaces of the shaft and the damper causes a thin fluid film to develop while the rotor turns. The load is supported by the hydrodynamic pressure in the fluid layer, which also affects the stiffness and damping properties of the damper.
- Pressure Profiles: Depending on the clearance between the rotor and the damper, the rotational speed, and the fluid characteristics, different pressures are applied to the damper's surfaces at different times. The performance of the damper under various operating situations must be understood by analyzing these pressure profiles.

II. Energy Dissipation Mechanisms:

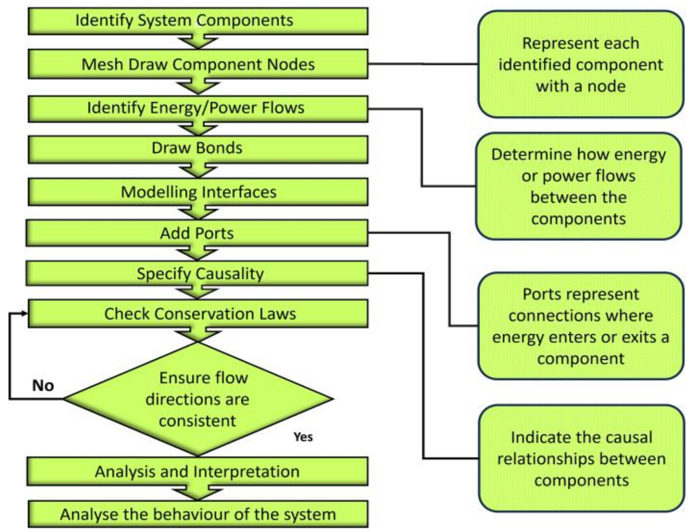
- Viscous Damping: As the fluid film in the SFD shears between the moving surfaces, viscous damping occurs, converting mechanical energy into heat. The reduction of vibration amplitudes and the production of heat is mostly attributable to this energy dissipation mechanism.
- Inertia Effects: In high-speed rotating equipment, inertia effects may also affect how energy is dissipated and how pressure is distributed. Advanced models take these influences into account to represent extra intricacies in the damper behaviour.

Engineers can accomplish the necessary vibration control and stability improvement in rotating equipment by optimizing the design of squeeze film dampers by simulating the squeeze film dynamics, pressure distribution, and energy dissipation processes. In order to develop effective and trustworthy computational frameworks for squeeze film damper analysis and design, advanced computational techniques, such as the Finite Element Method (FEM) and Bond Graph modelling, are used to gain a thorough understanding of the squeeze film behaviour and its interactions with the supported rotor.

BOND GRAPH MODELING FOR SQUEEZE FILM DAMPER

Bond Graph Basics and Tools:

The dynamic behavior of complex engineering systems, such as mechanical, electrical, hydraulic, and thermodynamic systems, is described and examined using the bond graph, a graphical modeling tool. It offers a consistent and organized way to depict the movement of energy through a system and the interactions between its many parts. The system is represented by a network of bonds and junctions in bond graphs, where bonds stand in for the flow of energy and junctions for the transfer of energy between various parts



Key Concepts in Bond Graph Modeling:

i. Bond graph elements are fundamental building blocks that reflect certain physical processes. Resistor (R) for energy dissipation, capacitor (C) for storage, and transformer (K) for energy exchange are a few examples of components.
ii. Ports: Ports are connection points on the elements through which energy can flow in and out. Ports are labeled with a plus sign (+) for energy flowing in and a minus sign (-) for energy flowing out.
iii. Causality: Bond graphs have a causal interpretation, which indicates that energy flows constantly from a source (e.g., a power supply) to a sink (e.g., a load). Causality aids in comprehending the cause-and-effect interactions between various factors.
iv. iv. Junctions: Junctions are sites on the bond graph where numerous bonds intersect, allowing energy to be exchanged between distinct components. Junctions are identified by a letter, and the energy flow at a junction is regulated by conservation principles. Bond Graph Tools:

Bond graphs may be made and analyzed using a variety of software programs. Before creating physical prototypes, these technologies aid engineers in comprehending the behavior of the system by facilitating the construction and simulation of complicated dynamic systems.

Here are additional procedures for modeling a squeeze film damper in a bond graph along with typical bond graph symbols[17]**:**

Identify the System Components:

Rotor: Represented by a "G" element (energy storage) with variables such as angular velocity (ω) and torque (τ).

Damper Sleeve: Represented by a "C" element (capacitance) with variables such as fluid pressure (p) and film thickness (h).

Fluid Film: Represented by a "TF" element (transformer) with variables for fluid flow rate (q) and pressure (p).

- Define Energy Ports:
  Rotor: e1 (effort) - Torque (τ), f1 (flow) - Angular velocity (ω).
  Damper Sleeve: e2 (effort) - Fluid pressure (p), f2 (flow) - Film thickness (h).
  Fluid Film: e3 (effort) - Pressure (p), f3 (flow) - Flow rate (q).
- Establish Bond Graph Elements:
  - "G" Element: Represents rotational energy storage.
  - "C" Element: Represents capacitance for fluid pressure. Symbol:
  - "TF" Element: Represents transformation between pressure and flow rate. Symbol:
- Assign Variables and Parameters:
  - Variables: Rotor: ω (angular velocity), τ (torque). Damper Sleeve: p (fluid pressure), h (film thickness). Fluid Film: p (pressure), q (flow rate).
  - Parameters: - Material properties, fluid properties, geometric characteristics, and operating conditions.
- Determine Causality and Interconnections:
  - Causality refers to the direction of energy flow in the bond graph elements. Effort variables cause the flow variables to change.
  - Connect the appropriate effort and flow variables for each element based on the physical interactions within the damper system.
- Validate and Refine the Model:
  - Compare the bond graph model's predictions with experimental or analytical data to ensure accuracy.
  - Make adjustments and refinements as needed to improve the model's accuracy and capture the damper's behavior.
- Perform Analysis and Simulation:

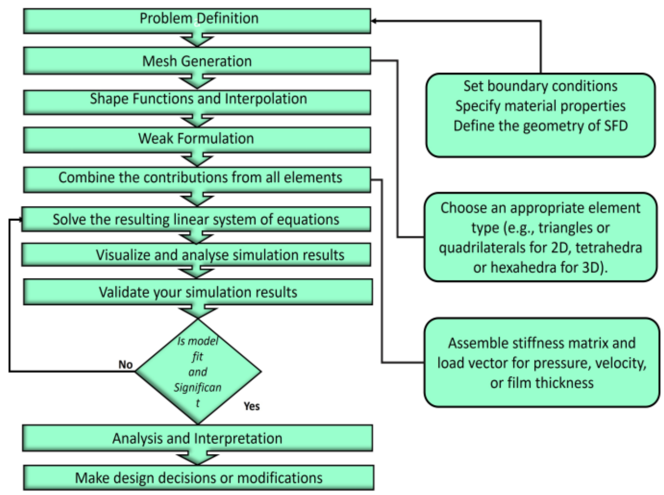
o Conduct numerous evaluations, including stability assessments, vibration analyses, and optimization studies, using the bond graph model.

o Simulate the behavior of the squeeze film damper under various operating circumstances and assess its effectiveness.

o the bond graph model's symbols may differ slightly based on the particular bond graph program or notation being used. In the conventional bond graph notation, the symbols mentioned above are often employed.

DEVELOPMENT OF THE COMPUTATIONAL FRAMEWORK

The supported rotor and squeeze film damper separate models are combined as part of the bond graph model integration procedure to build a comprehensive computational framework. The two models may communicate and share information without any problems because to the integration, which guarantees the system analysis's consistency and correctness.



The following steps are typically followed in the integration process:

a) *A thorough FEM model of the supported rotor should be created, taking into account both its geometrical and material characteristics.*
b) *Determine the boundary conditions depending on the restrictions and operational circumstances of the rotor, such as fixed supports or predetermined displacements.*
c) *Solve the FEM model to get the supported rotor's dynamic response.*
d) *Create a bond graph model of the squeeze film damper, accounting for its fluid dynamics, pressure distribution, and energy dissipation processes.*
e) *Include the essential bond graph components, including fluid flow, resistive, and capacitive components, to accurately depict the damper's behavior.*
f) *In the bond graph model, specify the pertinent characteristics, such as fluid viscosity, clearance, and pressure distribution.*
g) *Coupling methods: Employ coupling methods to time the simulation of the bond graph and FEM models. Identify the time-step synchronization and iteration strategies to bring the two models together. Up until a consistent and convergent solution is attained, iterate between the FEM and bond graph simulations.*

h) *Validation and Analysis: Verify the validity of the integrated computational framework by contrasting the simulation results with experimental data or analytical conclusions. Examine how the squeeze film damper and supported rotor performed under various operating scenarios and parameter changes. Evaluate the integration's success in capturing the system's dynamic interactions and energy transfer.*

7. ANALYTICAL INVESTIGATION AND RESULTS

- The analytical study presents findings on stability analysis, vibration control, and optimization of squeeze film damper parameters in a supported rotor system.
- The computational framework, combining Finite Element Method (FEM) and Bond Graph modelling techniques, accurately captures the complex behaviour of the system.
- Stability analysis identifies critical operating speeds and stability regions, ensuring safe and reliable operation.
- The squeeze film damper effectively controls vibrations, reducing mechanical wear and improving reliability.
- Optimization of damper parameters enhances damping effectiveness and system stability.
- The computational framework's precision is confirmed by comparison with experimental data and analytical solutions.
- In capturing the behaviour of the supported rotor system with the squeeze film damper, the computational framework is quite successful. The study highlights the framework's reliability, robustness, and utility in designing and optimizing squeeze film dampers. The framework contributes to improved rotating machinery performance and enhanced reliability.

8. DISCUSSION AND FUTURE DIRECTIONS

The report summarizes the main results and discusses future approaches for the combined use of Bond Graph and Finite Element Method (FEM) techniques in the modeling of squeezing film dampers. The following issues are covered: Validation and Limitations: The accuracy of the developed computational framework is discussed by comparing the simulation results with experimental data or analytical solutions. Limitations and potential sources of error in the modeling approach are identified and discussed.

- Effectiveness of the Computational Framework: It is assessed and examined how well the computational framework does at accurately capturing the behavior of the squeeze film damper. The benefits of the FEM and Bond Graph integration in providing a thorough comprehension of the dynamics and energy flow of the damper are highlighted.
- Sensitivity Analysis and Parameter Optimization: The study covers the value of carrying out sensitivity analysis to pinpoint the critical variables that have a substantial impact on the performance of the damper. It is investigated if parameter tuning may improve the squeeze film damper's overall performance and damping properties.
- Advanced Modelling Techniques: Future approaches for using advanced modeling methods, such as fluid-structure interaction (FSI) and Multiphysics modeling, are considered. It is underlined how useful these methods are for reproducing the squeeze film damper system's more intricate and realistic behaviour.
- The possibility of expanding the computational framework to represent squeeze film dampers in different rotor configurations, such as flexible rotors or multi-stage The successes of the established computational framework for simulating squeeze film dampers using FEM and Bond Graph methods are highlighted in the discussion section. As part of its efforts to improve the precision, applicability, and optimization capabilities of the modeling technique, it also offers insights into potential future research topics.

9. CONCLUSION

The following are the main conclusions and contributions of the analytical study on the creation of a computational framework for simulating the squeezing film damper through a supported rotor using Bond Graph and FEM techniques.:

- The study effectively illustrates the correctness and efficiency of the computational framework in simulating the behaviour of the squeeze film damper system. It offers a thorough comprehension of the damper's fluid dynamics, pressure distribution, and energy dissipation mechanisms.
- The supported rotor system with the squeeze film damper's dynamic stability was evaluated in the study using stability analysis. By identifying crucial operating speeds and situations that might cause instability, it helps in the design and optimization of dampers for higher system stability.
- Vibration analysis and control are made possible by the computational framework in the supported rotor system. Insights on the squeeze film damper's damping performance and vibration mitigation options may be gained by examining vibration amplitudes, resonance frequencies, and mode geometries.
- Optimization of Damper Parameters: In order to improve performance, this work looks at the optimization of squeeze film damper parameters. By analyzing the effects of crucial design elements like clearance, viscosity, and pressure distribution, ideal values that increase damping effectiveness and system stability may be found.
- investigates how to enhance the squeezing film damper's functionality by adjusting the damper's parameters. In order to identify the ideal values that improve damping

efficacy and system stability, it studies the impacts of important design factors such clearance, viscosity, and pressure distribution.

- ❖ The paper makes a contribution to the subject of rotating machinery by offering a solid computational foundation for simulating squeeze film dampers. The framework advances knowledge of damper behaviour, encourages design advancements, and aids in the creation of more dependable and efficient rotating machinery systems.

The squeeze film damper system's accurate modelling, stability analysis, ability to control vibration, parameter optimization, validation and comparison with experimental data, and overall contribution to the field of rotating machinery are, in summary, the analytical study's major findings and contributions.

REFERENCES

1. Bai H, Liu X, Li H, Zhang W, Meng G, Li M, Wang X (2014) Nonlinear dynamic characteristics of a large-scale tilting pad journal bearing-rotor system. JVE Int Ltd J vibroengineering 16:4045–4064
2. Zhou W, Qiu N, Wang L, Gao B, Liu D (2018) Dynamic analysis of a planar multi-stage centrifugal pump rotor system based on a novel coupled model. In: Journal of Sound and Vibration. Academic Press, pp 237–260
3. Hamzehlouia S, Behdinan K (2016) First order perturbation technique for squeeze film dampers executing small amplitude circular centered orbits with aero-engine application. pp 1–9
4. Perreault M, Student BAS, Hamzehlouia S, Behdinan K (2019) Application of Computational Fluid Dynamics for Thermohydrodynamic Analysis of High-Speed Squeeze-Film Dampers. Transantions Can Soc Mech Eng 43:1–49
5. Hamzehlouia S, Behdinan K (2018) Thermohydrodynamic modeling of squeeze film dampers in high-speed turbomachinery. SAE Interational J Fuels Lubr 11:129–146. https://doi.org/https://www.jstor.org/stable/26554702
6. Zeidan FY, San Andrés L, Vance JM (1996) design and application of squeeze film dampers in rotating macidnery. proc twenty-fifth Turbomach Symp 169–188. https://doi.org/https://doi.og/10.21423/R1649R
7. PIETRA D, ADILETTA (2002) The squeeze Film Damper over four decades of investigations. Part I: Characteristics and operating features. In: The Shock and vibration digest. Sage, Thousands Oaks, CA, pp 3–26
8. D. M. Smith (1964) Journal Bearing Dynamic Characteristics—Effect of Inertia of Lubricantle. In: Proceedings of the Institution of Mechanical Engineers. SAGE Publications Inc., pp 37–44
9. Dousti S, Cao J, Younan A, Allaire P, Dimond T (2012) Temporal and convective inertia effects in plain journal bearings with eccentricity, velocity and acceleration. J Tribol 134:. https://doi.org/10.1115/1.4006928
10. Zhao JY, Linnett IW, McLean LJ (1994) Stability and bifurcation of unbalanced response of a squeeze film damped flexible rotor. In: Journal of Tribology. pp 361–376
11. McLean LJ, Hahn EJ (1984) Stability of squeeze film damped multi-mass flexible rotor bearing systems. Trans ASME 107:402–409
12. McLean LJ, Hahn EJ (1983) Unbalance behavior of squeeze film damped multi-mass flexible rotor bearing systems. J Tribol 105:22–28. https://doi.org/10.1115/1.3254538
13. Barrett LE, Gunter EJ (1975) Dyrobes Rotordynamics Software https://dyrobes.com STEADY-STATE AND TRANSIENT ANALYSIS OF A SQUEEZE May 1975 FILM DAMPER BEARING FOR ROTOR STABILITY 6. Performing Organization Code 7. Author(s) 8. Performing Organization Report No
14. Zhao JY, Linnett IW, Mclean LJ (1994) Stability and Bifurcation of Unbalanced Response of a Squeeze Film Damped Flexible Rotor
15. Zhao JY, Linnett IW, McLean LJ (1994) Subharmonic and Quasi-Periodic Motions of an Eccentric Squeeze Film Damper-Mounted Rigid Rotor. J Vib Acoust 116:357–353. https://doi.org/https://doi.org/10.1115/1.2930436
16. El-Saeidy FMA (1998) Finite element modeling of a rotor shaft rolling bearings system with consideration of bearing nonlinearities. JVC/Journal Vib Control 4:541–602. https://doi.org/10.1177/107754639800400503
17. Pedersen E (2009) Rotordynamics and bond graphs: Basic models. Math Comput Model Dyn Syst 15:337–352. https://doi.org/10.1080/13873950903063116