DESIGN OF MECHANICAL DAMPER IN SEMI HERMATIC COMPRESSORS

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DECLARATION

I, **Okello Denis**, candidate for the Master of Science in Advanced Manufacturing Systems Engineering of Kyambogo University, declare that this is my original work and has never been presented for a degree in any other University, and no part of it is plagiarized work.

Sign: ..... Date: .....

APPROVAL

This Master of Science Dissertation, prepared and submitted by Okello Denis in partial fulfilment of the requirements for the Master of Science in Advanced Manufacturing Systems Engineering Degree of Kyambogo University, has been supervised and is ready for submission for an academic award.

Sign..... Date.....

Dr. Maureen Nalubowa

Sign..... Date.....

Eng. Dr. Kangwagye Samuel

DEDICATION

This dissertation is dedicated to my family, whose love and support have been my guiding light. To my mentors, who encouraged me to push harder and beat deadlines.

To my friends, who stood by me throughout this dissertation, reminding me to keep up and track my progress.

And finally, to everyone who contributed to this dissertation, may you continue to pursue, to question, and to inspire.

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ACRONYMS

3D	:	Three-Dimensional
CAD	:	Computer-Aided Design
CFD	:	Computational Fluid Dynamics
FEA	:	Finite Element Analysis
FFT	:	Fast Fourier Transform
HVAC:		Heating, Ventilation, and Air Conditioning
K	:	Kelvin (unit of temperature)
R&D	:	Research and Development
RPM	:	Revolutions Per Minute
TMD	:	Tuned Mass Damper

ABSTRACT

Excessive vibrations, especially in semi-hermetic compressors, can lead to performance degradation, increased maintenance costs, and potential system failures. Current techniques, such as vibration isolation spring mounts and rotor balancing, are found to be ineffective in addressing the dynamic operating conditions of these compressors This dissertation investigated the vibration characteristics of semi-hermetic compressors, which are critical components in refrigeration and air conditioning systems. The primary sources of vibration, including imbalance, misalignment, and resonance, emphasized the need for effective vibration suppression methods. The methodology focused on design of a mechanical damper that adapts to the varying operational conditions of semi-hermetic compressors, enhancing their reliability and efficiency. Utilizing 3D SolidWorks simulations, a detailed frequency analysis of the compressor's vibration spectrum under different frequencies and damping ratios was conducted. Analysis results revealed that there is excessive vibration during compressor start up and shutdown, there is a torsional kick, coupled with resonance. This led design of a damper which was integrated to the spring and a vibration frequency analysis was repeated using solid works ,this time with a spring damper system, the results revealed complete vibration suppression in both compressor start up and shut down, indicating the ability of the damper to handle dynamic vibration conditions like the cyclic nature of the semi hermetic compressor, the suction and discharger stroke, refrigerant fluctuating pressure and so forth ,the proposed damper design was validated through mathematical modeling, demonstrating its effectiveness in reducing vibration amplitudes across a range of frequencies. The findings highlighted the importance of advanced damping technologies in improving the operational longevity and energy efficiency of semi-hermetic compressors, and therefore contributing to the sustainability of refrigeration and air conditioning systems. This research did not only address the technical challenges associated with compressor vibrations but also provided a foundation for future innovations in vibration suppression technologies.

Keywords: semi-hermetic compressors, vibration analysis, vibration suppression, mechanical damper design, SolidWorks simulation, operational efficiency, refrigeration systems.

CHAPTER ONE: INTRODUCTION

1.1 Background

In today's commercial environments especially in large scale supermarkets, air conditioning plays a critical role, as demands for reliable cooling systems continue to rise, their performance becomes increasingly vital, at the center of these cooling systems are semi hermetic compressors. These compressors undergo challenges of undesirable vibration.

Vibration in semi-hermetic compressors presents a notable concern due to its potential to compromise performance and induce system failures (Ab Ghani et al., 2023). This vibration often stems from various sources including imbalance, misalignment, worn bearings, liquid slugging, and resonance, leading to detrimental effects such as reduced efficiency, accelerated component wear, increased noise levels, and structural damage (Kumar et al., 2023). To mitigate these risks, regular vibration analysis, balancing procedures, alignment checks, and adherence to proper installation and maintenance protocols are imperative to ensure the dependable operation of semi-hermetic compressors (Kancham, 2018). vibration in semi-hermetic compressors can significantly impact the performance and reliability of refrigeration and air conditioning systems. Excessive vibration can accelerate wear and tear on critical components such as bearings, piston rings, and valves, leading to increased maintenance requirements and reduced operational lifespan (Yahya et al., 2023). vibrations can compromise the efficiency of the compressor by increasing frictional losses and reducing energy transfer efficiency, thereby negatively impacting overall system performance (Yang et al., 2024). Furthermore, vibrations often produce noise, which can be disruptive in both residential and commercial settings, affecting comfort levels (Seyedi, 2024). Additionally, severe vibrations can pose a risk of

structural damage to the compressor housing and associated piping, potentially resulting in costly repairs (Chu et al., 2024a).

Currently, several methods are employed to suppress vibration in semi-hermetic compressors, ensuring their reliable operation in refrigeration and air conditioning systems. One common approach is the utilization of vibration isolation mounts or dampers, to suppress mechanical vibrations transmitted from the compressor to surrounding structures(Liu et al.,2024).

current vibration suppression methods for semi-hermetic compressors are limited and does not focus on addressing dynamic operational conditions and environmental factors that can contribute to vibration issues. The existing techniques such as vibration isolation mounts are not effective, and do not adequately account for variations in compressor operating conditions, such as changes in load, speed, ambient temperature and resonance which can influence compressor dynamics and vibration characteristics (Srinivas et al., 2018).

1.2 Semi-Hermetic compressor at Carefour Supermarket under study



Figure 1.1: Semi-hermetic compressor vibration eliminator removed and replaced with copper pipe

The semi hermetic compressor unit above consists of compressor manifold, piping system, electric motor, pipe, base frame, pipe supports and anti-vibration spring mount. The semi hermetic compressor is connected on its termination point to the piping systems and runs a central air conditioning system at Carrefour supermarket Lugogo branch. The vibration on this compressor led to the failure of the vibration eliminator which was then cut off and replaced with copper pipe as shown in the area circled in green.

1.3 Problem Statement

In refrigeration and air conditioning, semi-hermetic compressors are key components that demand continuous improvement for optimal performance. One of the persistent challenges faced in their operation is the presence of undesirable vibrations, arising from various mechanical and dynamic factors.

The vibrations generated during the operation of semi-hermetic compressors pose quite a number of challenges in its performance. These vibrations, if left unsuppressed, led to a number of issues including accelerated wear and tear, diminished energy efficiency, and increased noise levels refrigerant leakages and broken refrigerant pipes. Current damping and isolation technologies, are not effective in traditional compressor designs, and fall short in providing an optimal solution for the unique vibrational characteristics common in semi-hermetic compressors.

Hence the need for the design for mechanical damper in semi hermetic compressor.

1.4 Research Objectives

1.4.1 Main Objectives

To design a mechanical damper that can adapt to semi-hermetic compressor dynamic operating conditions, for effective vibration suppression.

1.4.2 Specific Objectives

(i) To conduct a detailed frequency analysis of the vibration spectrum generated by the current semi-hermetic compressor under various operating conditions.

(ii) To determine the design components and parameters.

(iii) To develop a layout of mechanical damper design.

(iv) To validate the proposed mechanical damper design using a mathematical model.

1.5 Research Questions

(i) What are the dominant vibration frequencies exhibited by the semi-hermetic compressor under different operating conditions?

(ii) Which design components and parameters most significantly affect the vibration behavior of semi-hermetic compressors?

(iii) How can these parameters be quantified and optimized to reduce vibration levels?

(iv) What design layout of a mechanical damper is most effective in mitigating compressor vibrations?

(v) How can the damper be integrated into the compressor system without compromising efficiency or reliability?

(vi) How accurately does the mathematical model predict the vibration reduction achieved by the proposed damper design?

1.6 Justification

The design of a mechanical damper to suppress vibrations in semi-hermetic compressors is a critical research work with extensive implications for various industrial applications. Semi-hermetic compressors play a crucial role in refrigeration and air conditioning systems, Without the incorporation of a mechanical damper, semi-hermetic compressors face several bottlenecks that compromise their performance and reliability. Excessive vibration levels propagate through the housing and connected piping, causing structural fatigue, cracks, and accelerated wear of bearings, valves, and seals, which shortens equipment lifespan and increases the frequency of part replacements. These vibrations also introduce mechanical inefficiencies that raise energy consumption, while simultaneously generating disruptive noise that signals instability and raises safety concerns. The cumulative effect is reduced reliability, frequent downtime, and escalating maintenance costs, all of which undermine cost-effectiveness for industries that depend on continuous refrigeration and HVAC operations. This research will pave way for technological innovations that can elevate the competitiveness and efficiency of industries utilizing semi-hermetic compressors.

1.7 Significance of the study.

Uncontrolled vibrations in semi-hermetic compressors pose challenges that impact performance, energy consumption, and maintenance costs. By addressing these issues through an innovative mechanical Damper, this research has the capacity to extend the operational lifespan of compressors, reduce energy consumption, and minimize maintenance requirements. The economic implications are substantial, with potential cost savings. This study is not only looking at advancing compressor technology but also holds broader implications for improving

overall system efficiency and meeting the demands of a sustainable and technologically advanced industrial landscape.

1.8 Scope of the Study

The research scope for the design of a mechanical Damper to suppress vibration in semi-hermetic compressors includes investigation into the dynamics, materials, and structural elements involved in achieving effective vibration control. The study will explore the vibrational characteristics of semi-hermetic compressors under various operational conditions, considering the frequency and amplitude variability. It will involve the exploration and optimization of different materials for the Damper, focusing on properties such as elasticity, damping, and tensile strength, with the aim of maximizing vibration suppression while maintaining mechanical integrity. The research will also investigate various structural elements, including geometry, size, and configuration, to understand their influence on Damper ability to effectively suppress vibrations. Modeling and simulation techniques will be employed to analyze the dynamic response, enabling predictive analysis and optimization for diverse operational scenarios.

1.9 Conceptual Framework

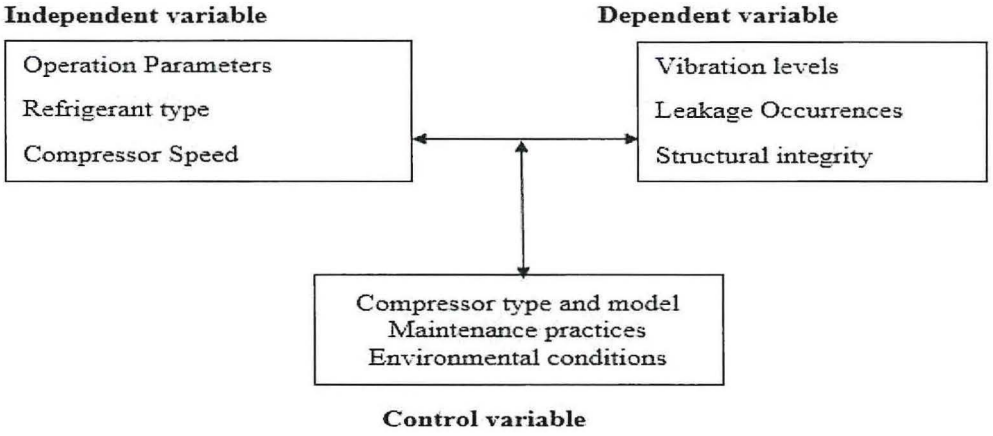


Figure 1.2: Conceptual Framework of the Study

CHAPTER TWO: LITERATURE REVIEW

2.1 Overview of Semi-Hermetic Compressors

Semi hermetic compressors are types of compressors that is widely used in refrigeration and air-conditioning systems. According to Refrigeration and air conditioning, Heating, Refrigeration Certification Board Brezina, (2017), noted that Semi hermetic compressors are characterized by a shell that surrounds the compressors motor and pump the shell is typically made of steel or cast iron and is designed to provide a strong, leak tight enclosure for the compressor's internal components.

2.1.1 Types of Semi-Hermetic Compressors

Reciprocating Semi-Hermetic Compressors: According to Liang, (2017), these compressors utilize a piston mechanism to compress the refrigerant. The piston moves within a cylinder to compress the gas in cycles. Reciprocating compressors are recognized for their robust design and capability to manage high-pressure applications, making them suitable for small to medium-sized refrigeration systems.

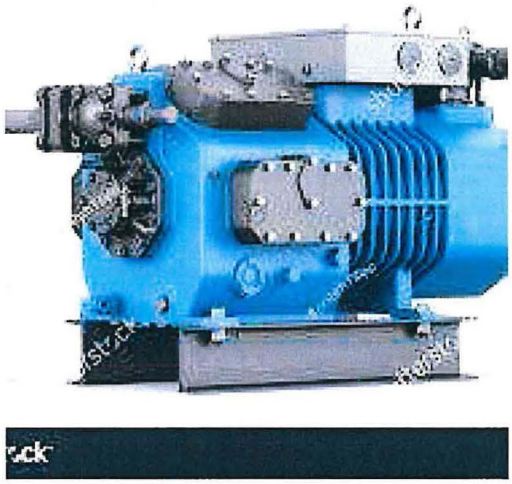


Figure 2. 1: Reciprocating Semi Hermetic compressor

Applications: noted that reciprocating compressors are commonly used in refrigeration systems for cold storage, commercial refrigerators, and HVAC units, including those in supermarkets and refrigerated transportation systems.

Scroll Semi-Hermetic Compressors: Sung et al., (2020) explained that scroll compressors feature two spiral scrolls—one fixed and one moving—that compress the refrigerant gas as the moving scroll orbits. These compressors are generally quieter, more efficient, and have fewer moving parts compared to reciprocating types.



Figure 2. 2: Scroll semi hermetic compressor

Applications: As stated by El Samad et al., (2024), scroll compressors are frequently applied in residential and commercial air conditioning systems, heat pumps, and medium-temperature refrigeration applications due to their efficiency and low noise output.

Screw Semi-Hermetic Compressors: Islam, (2023) described screw compressors as utilizing two interlocking helical rotors to compress refrigerant. They are capable of managing large refrigerant volumes and continuous compression, rendering them particularly durable and efficient for large systems.



Figure 2. 3: screw semi hermetic compressors

Applications: Lv et al., (2021) indicated that these compressors are commonly found in industrial refrigeration systems, such as those in food processing plants, pharmaceutical industries, and large HVAC installations, where high capacity and energy efficiency are critical.

Centrifugal Semi-Hermetic Compressors: Jaatinen-Värri et al., (2024) explained that centrifugal compressors employ a rotating impeller to accelerate refrigerant gas outward, compressing it as it decelerates. They are known for their high efficiency in high-volume, low-pressure applications.

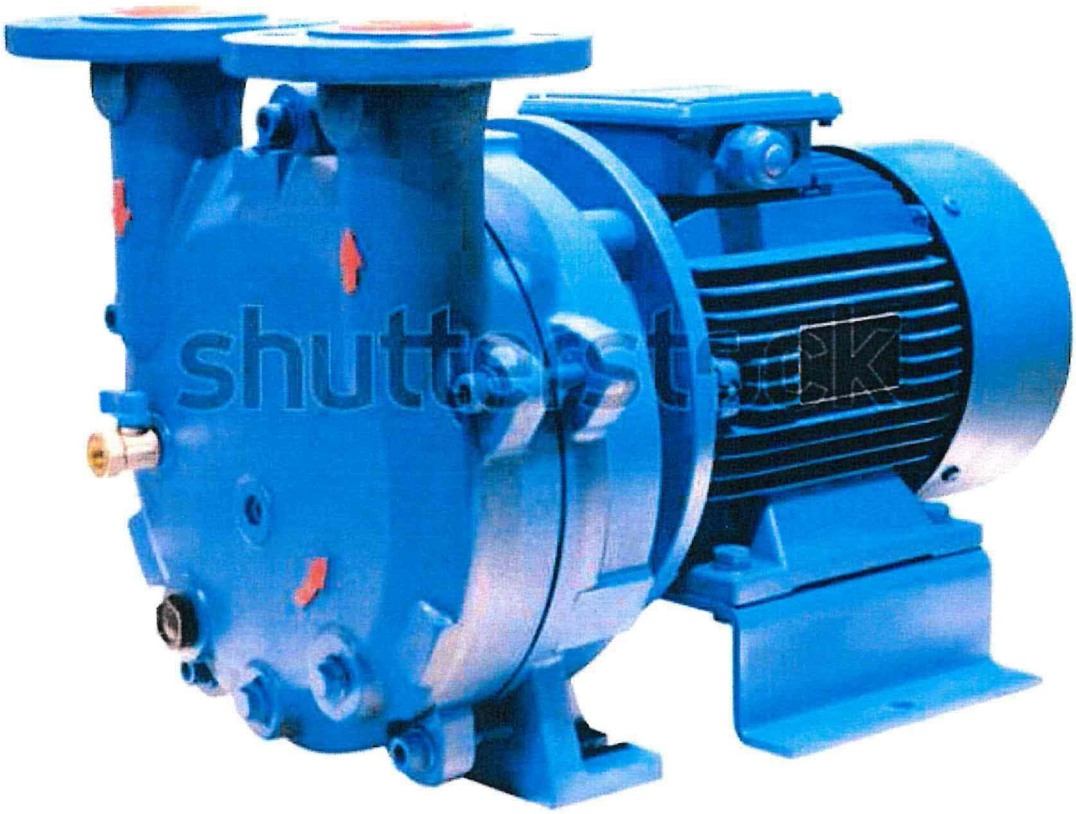


Figure 2. 4: Centrifugal Semi hermetic compressor

Applications: According to Mojaddam & Pullen, (2019), centrifugal compressors are often utilized in large-scale commercial air conditioning systems, such as those in airports, hospitals, and office buildings, where they manage large loads with high efficiency

2.1.2 Applications of Semi-Hermetic Compressors

Commercial Refrigeration: According to Shen et al., (2021) semi-hermetic compressors are frequently employed in commercial refrigeration, particularly in supermarkets, restaurants, and grocery stores. Their serviceability and repairability make them ideal for high-demand environments where minimizing downtime is critical.

Industrial Refrigeration: Ireland, (2015) noted that in industries such as food processing, chemicals, and pharmaceuticals, semi-hermetic compressors are essential for process cooling, storage refrigeration, and blast freezing. Screw compressors, in particular, are favored in these applications due to their capability to handle large capacities with high efficiency.

HVAC Systems: As indicated by Li et al, (2015), semi-hermetic compressors especially scroll and centrifugal types—are widely used in HVAC systems for large buildings like hotels, hospitals, and office complexes. Their efficiency and quieter operation make them suitable for environments where noise reduction is a priority.

Cold Chain Logistics: According to Minetto et al., (2023), semi-hermetic compressors are utilized in refrigerated transport systems, such as trucks and containers, to ensure that perishable goods are maintained at optimal temperatures. Their reliability and ease of maintenance are essential for this critical application.

Marine Applications: Fabris et al, (2023) explained that semi-hermetic compressors are employed in marine settings for cooling cargo holds, refrigeration of perishable goods, and air conditioning. Their durability and ease of maintenance are vital, particularly when access to replacement parts may be limited at sea.

2.1.3 Common Issues Associated with Vibration in Semi-Hermetic Compressors

According to Tian et al. (2019), issues associated with vibration in semi-hermetic compressors can lead to operational inefficiencies, wear and tear, or even damage to critical components. Some of the most frequently encountered problems include:

Component Fatigue and Failure: Prolonged vibration can cause fatigue in compressor components such as shafts, bearings, and valves, leading to premature failure. This fatigue weakens materials, especially in rotating parts, where cyclic stresses accumulate over time (Mondal, 2024a).

Increased Noise Levels: Vibration often correlates with elevated noise levels, which can affect the surrounding environment and may indicate underlying mechanical problems. Noise can stem from imbalances in moving parts or worn bearing (CİNGİZ et al., 2021).

Bearing Wear: Excessive vibration accelerates wear in bearings, reducing their lifespan and leading to misalignment or even catastrophic failure. Bearings are critical in maintaining the stability of rotating components, and their degradation can result in increased friction and vibration (Xu et al., 2023a).

Shaft Misalignment: Misalignment between the motor and compressor shaft is a common source of vibration. This misalignment causes uneven loading on the components, further increasing vibration and potentially causing damage to couplings and seals (Mondal, 2024b).

Seal Damage and Refrigerant Leaks: Vibrations can cause mechanical seals to wear out faster, leading to refrigerant leaks in the compressor system. This not only affects the efficiency of the cooling system but can also result in environmental and safety concerns (Francis et al., 2017).

Electrical Motor Problems: Vibration can be both a cause and a symptom of electrical issues in the motor, such as unbalanced phases or winding problems. These electrical issues can create uneven torque and cause further mechanical vibrations, forming a cycle of degradation (Ye et al., 2020).

Loosening of Fasteners and Components: Continuous vibration can loosen bolts, fasteners, and other critical components, leading to further mechanical instability. This can result in more severe failures if not addressed promptly (Huang et al., 2022).

2.1.4 Impact of Vibration on Compressor Performance and Lifespan

The impact of vibration on compressor performance and lifespan is significant, as it can lead to a variety of operational and mechanical problems.

Decreased Efficiency: According to Smith Appadoo (2021), vibrations often result in inefficient operation, as the compressor components do not function optimally. Misalignments, loosened parts, or wear caused by vibration can cause energy losses, reducing the overall performance of the system. Additionally, imbalances in rotating parts can increase friction and resistance, leading to greater energy consumption and lower efficiency (Julaha et al., 2019).

Component Wear and Tear: Vibration accelerates the wear of critical components such as bearings, shafts, and seals. This increased wear shortens the compressor's operational lifespan and necessitates more frequent maintenance or replacement of parts. In particular, bearings, which are crucial for supporting the rotation of shafts, are prone to failure under persistent vibration, leading to breakdowns (Xu et al., 2023b).

Increased Downtime and Maintenance Costs: Excessive vibration can cause unexpected breakdowns, resulting in unplanned downtime. The increased frequency of repairs or replacements leads to higher operational costs and longer periods of inactivity, impacting overall productivity (Park et al., 2023).

Damage to Mechanical Seals and Refrigerant Leaks: Vibrations can damage mechanical seals, causing refrigerant leaks, which reduce the cooling capacity of the system. This not only affects the efficiency but also contributes to environmental concerns due to refrigerant loss (Joshi et al., 2002). Such leaks can also require more frequent maintenance and refills, adding to the operational costs.

Resonance and Catastrophic Failures: According to Haba et al. (2018), in severe cases, mechanical resonance can amplify the effects of vibration, leading to catastrophic failures of components. When the natural frequency of a component matches the frequency of the vibration, it can cause large oscillations that lead to cracking, breakage, or even complete system failure.

2.2 Frequency Analysis Techniques

According to Lyu et al (2023), frequency analysis is a fundamental technique in mechanical systems used to study and understand the behavior of structures or components under dynamic loading. It involves analyzing the natural frequencies and the response of a system to external forces to predict and mitigate potential failures. Here are some key aspects of frequency analysis:

Natural Frequency and Resonance: Every mechanical system has one or more natural frequencies, which are the frequencies at which the system tends to vibrate when disturbed. If the frequency of an external force matches one of the system's natural frequencies, resonance occurs, significantly amplifying vibrations. Resonance can lead to catastrophic failures, as even small forces can induce large oscillations, causing mechanical damage (Oral et al., 2023).

Mode Shapes: According to Mendonça et al. (2022), frequency analysis helps determine not only the natural frequencies but also the mode shapes of a system. Mode shapes describe the specific deformation patterns of a system at its natural frequencies. Understanding these shapes is critical for identifying areas of high stress or potential failure points in mechanical components.

Fourier Transform: A common method in frequency analysis is the Fourier Transform, which decomposes a time-domain signal (such as a vibration measurement) into its frequency components. This allows engineers to identify dominant frequencies and their amplitudes within the system, providing insight into potential sources of vibration and instability (Brandt, 2019).

Frequency Response Function (FRF): The FRF is a mathematical representation that describes how a mechanical system responds to a range of frequencies. By applying a known input force at varying frequencies, engineers can measure the system's output response and create an FRF, which helps in diagnosing issues like resonance, misalignment, or imbalance in rotating machinery (Rodrigues et al., 2016).

Damping Characteristics: Frequency analysis also reveals how damping affects the vibration behavior of a system. Damping is the process by which energy is dissipated in a vibrating system. High damping reduces the amplitude of vibrations, even at resonant frequencies, making it a crucial factor in controlling and minimizing vibrations in mechanical systems (Wang et al., 2017).

Application in Preventive Maintenance: In mechanical systems, frequency analysis is used in condition monitoring and predictive maintenance. By regularly monitoring the frequency

spectrum of a machine's vibrations, deviations from normal operating conditions can be detected early, helping to prevent failures before they occur (Hassin, 2017).

2.2.1 Tools and Methods for Vibration Spectrum Analysis

According to Mohd Ghazali & Rahiman (2021), vibration spectrum analysis is a powerful diagnostic tool used to assess the health of mechanical systems by analyzing vibration signals. It helps in detecting faults such as imbalance, misalignment, bearing defects, and resonance in rotating machinery. There are various tools and methods used in vibration spectrum analysis:

Accelerometers: Accelerometers are the primary sensors used in vibration analysis. They are mounted on machinery to detect the amplitude and frequency of vibrations. These sensors measure acceleration, which can then be integrated to calculate velocity and displacement. Accelerometers provide highly accurate data, and their compact size allows them to be placed in critical locations on the equipment (Varanis et al., 2018).

Fast Fourier Transform (FFT): The Fast Fourier Transform is one of the most widely used techniques for analyzing vibration data. It converts time-domain vibration signals into the frequency domain, breaking the vibration into its constituent frequencies. This method helps in identifying which frequencies are dominant and where potential problems such as imbalance, misalignment, or bearing defects exist (Goyal & Pabla, 2016). The resulting vibration spectrum provides a clear picture of the machinery's condition based on frequency and amplitude.

Envelope Detection: According to Leite et al. (2017), envelope detection is a specialized technique used to identify early-stage bearing faults. Bearings often generate high-frequency signals when they begin to fail, which can be difficult to detect using standard FFT. Envelope

detection amplifies and demodulates these high-frequency signals, making it easier to detect defects in bearings before they lead to catastrophic failures.

Order Tracking: Order tracking is a technique used to analyze vibration data in machines with varying rotational speeds, such as turbines or compressors. This method synchronizes the vibration data with the rotational speed, which is particularly useful for diagnosing problems like imbalance or misalignment in systems where speed fluctuates during operation. It enables better tracking of faults related to specific rotating components (Tiboni et al., 2022) .

Wavelet Transform: Wavelet transform is an advanced method that provides both time and frequency information simultaneously. Unlike FFT, which only analyzes frequency, wavelet transform can be used to detect transient events and non-stationary signals, making it ideal for detecting faults that occur over short periods, such as impacts or shocks in gearboxes or motors (Duan et al., 2016). It is particularly useful in complex machinery with variable operating conditions.

Vibration Data Loggers and Analyzers: Modern vibration data loggers and analyzers are equipped with software tools to simplify spectrum analysis. These devices collect vibration data over time and provide real-time spectrum analysis using built-in algorithms. Some advanced models are equipped with wireless sensors, allowing for continuous monitoring and remote analysis, which is essential for preventive maintenance in large-scale industrial systems (Blanco et al., 2016).

Phase Analysis: Phase analysis is another important method that compares the relative motion of different parts of the machinery. By analyzing the phase relationships between vibration signals at different points, engineers can pinpoint specific problems such as misalignment or

looseness. This technique is often used in conjunction with FFT to provide a more complete picture of the machinery's dynamic behavior (Dutra & Deschamps, 2015).

2.2.2 Case Studies of Frequency Analysis in Similar Mechanical Systems

Frequency analysis has been successfully applied in various mechanical systems to diagnose faults, improve efficiency, and extend the lifespan of equipment. Several case studies demonstrate its practical applications in industrial settings, particularly in rotating machinery, compressors, and turbines.

Rotating Compressors in the Oil and Gas Industry: In an oil refinery, frequency analysis was employed to diagnose high vibration levels in a rotating compressor. The FFT spectrum showed a dominant frequency corresponding to the machine's running speed, with additional harmonics indicating mechanical looseness and misalignment. A more detailed order tracking analysis further confirmed misalignment in the shaft coupling. Corrective realignment reduced vibration amplitudes, which not only improved performance but also prevented potential downtime due to failure (Wang et al., 2023).

Vibration Analysis in Centrifugal Pumps: A chemical plant experienced recurring failures in their centrifugal pumps, and frequency analysis was used to diagnose the problem. The vibration data showed a high amplitude at a frequency twice the rotational speed, which is characteristic of cavitation in pumps. Based on this analysis, engineers adjusted the pump's operational parameters, reducing the cavitation and associated vibrations. As a result, the pumps operated more efficiently, and the maintenance frequency dropped (Al-Obaidi, 2019).

Failure Prevention in HVAC Systems: In a large commercial building, frequency analysis was applied to diagnose abnormal vibrations in the HVAC system's compressor. The FFT revealed

a peak at the natural frequency of the system, indicating resonance. By stiffening the mounts and adjusting the compressor's operational speed, the resonance condition was mitigated, thereby reducing wear and extending the system's operational life (Chu et al., 2024).

Bearing Failure Detection in Rolling Mills: In a steel manufacturing plant, frequency analysis was used for early detection of bearing failures in rolling mills. Envelope detection, a specialized form of frequency analysis, was employed to monitor high-frequency signals generated by early-stage bearing defects. This technique allowed the detection of subtle defects long before they would have caused a breakdown. Scheduled bearing replacements based on these findings helped avoid costly unplanned downtime and prolonged the lifespan of the equipment (Nirwan & Ramani, 2022).

2.3 3D SolidWorks Simulation for Vibration Analysis

2.3.1 Introduction to 3D SolidWorks and Its Simulation Capabilities

SolidWorks is a powerful 3D computer-aided design (CAD) software widely used in engineering and manufacturing for product design and simulation. Developed by Dassault Systems, SolidWorks provides tools for creating detailed 3D models, assemblies, and 2D drawings. Its simulation capabilities, embedded within the software, allow engineers to analyze how designs will perform under real-world conditions before physical prototypes are made, significantly improving the design process.

2.3.2 3D Modelling in SolidWorks

At its core, SolidWorks excels in creating parametric 3D models using sketches, features, and constraints. Users can build complex parts and assemblies by defining geometric relationships and dimensions, enabling easy modifications and updates throughout the design process (Tran,

2017). Its intuitive interface and powerful feature set make it suitable for designing anything from small mechanical parts to large industrial assemblies. SolidWorks offers an array of modeling tools, including:

- Extrusions, lofts, and sweeps for generating complex shapes.
- Fillets and chamfers to modify edges.
- Pattern tools for repetitive features like holes or slots.

These features allow users to rapidly develop highly detailed 3D models while maintaining parametric control, making it a go-to software in many industries (Zeid, 2021).

2.3.3 Assembly and Motion Analysis

SolidWorks' assembly environment enables users to combine individual parts into complete systems, applying mates and constraints to define the relationships between components. The assembly module can handle both small and large assemblies, allowing for the design of complex systems such as engines, robotics, or large-scale industrial equipment. Motion analysis is a key feature that simulates the movement of parts within an assembly. Engineers can analyze how components interact under different forces, torques, or constraints, helping to identify potential collisions, interferences, or misalignments in the design (Alam & Cao, 2023). By simulating motion, users can optimize the design to ensure proper functionality before moving to the prototype phase.

2.3.4 Simulation Capabilities

SolidWorks integrates several simulation tools that allow for virtual testing of designs. These simulations help engineers predict how a design will behave under various conditions such as

stress, temperature, fluid flow, and vibration. The primary simulation capabilities of SolidWorks include:

Finite Element Analysis (FEA): SolidWorks Simulation provides FEA for structural analysis, allowing users to test the strength and durability of parts under different loads, forces, and constraints. By meshing the model into smaller elements, engineers can calculate stresses, strains, and deformations, helping to identify weak points in the design (Mustapha, 2022).

Thermal Analysis: The software also includes thermal simulation, which allows users to study how heat affects materials and components. This is especially useful in industries like electronics, where heat management is critical to ensuring the longevity of components (Marshall et al., 2019).

Computational Fluid Dynamics (CFD): Using SolidWorks Flow Simulation, engineers can analyze fluid flow and heat transfer within and around parts and assemblies. Computational Fluid Dynamics (CFD) is essential for designing systems like ventilation, cooling systems, and aerodynamic components. It provides insights into fluid behavior and performance without the need for physical testing (Gavilan et al., 2020).

Vibration and Fatigue Analysis: Vibration analysis tools in SolidWorks help determine how a part or assembly will react to oscillatory forces. Engineers can evaluate resonance, frequency response, and damping characteristics. Additionally, fatigue analysis predicts how a part will behave under repeated loading, which is crucial in applications such as automotive and aerospace industries, where parts experience cyclic stresses (Jaeger, 2023).

2.3.5 Design Validation and Optimization

SolidWorks' simulation capabilities are not just about testing; they also offer design optimization features. Users can run design studies where parameters like material thickness, load conditions, or geometry are varied to find the optimal configuration that meets performance criteria while minimizing weight or cost. This design optimization is a crucial aspect of modern engineering, helping to improve efficiency and sustainability (Suresh, 2021).

2.3.6 Previous Research and Applications of SolidWorks in Vibration Studies

SolidWorks has been widely utilized in various research and industrial applications to conduct vibration studies, owing to its robust simulation capabilities, particularly with its integrated SolidWorks Simulation (FEA tool). Researchers and engineers use SolidWorks for analyzing mechanical vibrations to predict performance, diagnose issues, and optimize designs. These applications span industries such as automotive, aerospace, and manufacturing, where accurate vibration analysis is critical for ensuring structural integrity and operational efficiency.

Modal and Harmonic Vibration Analysis in Aerospace Components: One of the prominent applications of SolidWorks in vibration studies is in the aerospace industry. Researchers have used SolidWorks to perform modal analysis on aircraft components such as turbine blades and fuselage sections to identify natural frequencies and associated mode shapes. For example, a study by (Naeem, 2024) focused on optimizing the design of aircraft wings by conducting a modal analysis using SolidWorks. The researchers identified the critical natural frequencies at which the wings were prone to resonance and made design adjustments to increase the structure's rigidity, thereby avoiding resonance-related failures. Similarly, harmonic analysis was used to evaluate the frequency response of engine components subjected to oscillatory forces during operation. SolidWorks provided a clear understanding of how these components

vibrated under varying frequencies, allowing for better materials selection and design improvements (Saikiran & Arunagiri, 2019).

Vibration Analysis in Automotive Systems: The automotive industry frequently uses SolidWorks for vibration studies, especially in analyzing the behavior of mechanical parts like crankshafts, suspension systems, and engine mounts. Research by (Georgiev & Kunchev, 2018) demonstrated the use of SolidWorks to analyze the vibrational response of an automotive suspension system. By applying dynamic loads and conducting a harmonic response analysis, the researchers were able to determine the critical frequencies that caused excessive vibrations, leading to the redesign of the suspension system to mitigate these issues. In another study, SolidWorks was employed to optimize the design of engine mounts by reducing vibration transmission from the engine to the chassis. Harmonic analysis revealed specific frequencies where the mounts transmitted high levels of vibration, which were addressed by changing the material and geometry of the mounts. This led to reduced noise, vibration, and harshness (NVH) in the vehicle, improving passenger comfort (Achour et al., 2020).

2.3.7 Vibration and Structural Integrity in Industrial Machinery

In manufacturing and heavy machinery, SolidWorks has been widely adopted for vibration analysis to ensure structural integrity and operational reliability. For instance, in the design of rotating machinery such as pumps and compressors, SolidWorks was used to perform frequency analysis to identify vibration-related issues. A study by (Rodrigues et al., 2016) utilized SolidWorks to analyze the vibration of a centrifugal pump operating at different speeds. By conducting modal and harmonic analysis, the researchers pinpointed the frequencies at which the pump experienced excessive vibrations and recommended changes to the rotor design and shaft alignment.

In a related application, SolidWorks was applied in the vibration analysis of gearboxes in industrial equipment. Researchers employed modal analysis to evaluate the natural frequencies of the gears and bearings, identifying specific conditions where resonance occurred. The findings led to the optimization of gear tooth profiles and bearing selection, significantly improving the lifespan of the gearbox and reducing maintenance costs (Palmeth et al., 2024).

2.4 Research in Vibration Damping

Several studies have also focused on how SolidWorks can be used to improve vibration damping in materials and structures. For example, in the field of composite materials, SolidWorks has been used to simulate how different materials absorb and dissipate vibrational energy. By analyzing the damping properties of composite structures, researchers could design materials that effectively reduce vibration in high-performance applications such as aerospace and automotive parts (Scalzo et al., 2023).

Similarly, vibration isolation systems in mechanical structures have been optimized using SolidWorks. By simulating how isolation mounts and dampers perform under vibrational forces, engineers have been able to design more efficient systems that reduce the transmission of harmful vibrations to sensitive components or structures (Al Rifaie et al., 2022).

2.4.1 Principles of Vibration Damping

Vibration damping is a technique used to reduce or eliminate unwanted vibrations in mechanical systems. According to Feng (2023), vibration damping involves the conversion of kinetic energy into heat energy through internal friction or other mechanism, which is then dissipated. The primary goal of damping is to reduce the amplitude of oscillations in mechanical structures over time, preventing resonance and minimizing wear and tear

2.4.2 Basic Concepts of Vibration Damping and Suppression

Vibration damping and vibration suppression are essential concepts in mechanical engineering, aimed at reducing the amplitude of vibrations in mechanical systems to prevent structural damage, enhance performance, and improve operational stability. These techniques are widely applied across various industries, including automotive, aerospace, and manufacturing, to mitigate the adverse effects of vibrations.

2.4.3 Types of Vibration Damping

Viscous Damping: In this form of damping, the resistive force is proportional to the velocity of the vibrating object. It involves the use of fluids (such as oil or air) to absorb kinetic energy from the moving part. This type of damping is common in systems like shock absorbers in automobiles, where hydraulic fluid dissipates vibrational energy as heat (Lenggana et al., 2021).

Coulomb Damping (Friction Damping): This type of damping occurs due to dry friction between two surfaces in contact. The frictional force remains constant regardless of velocity, dissipating energy as heat. Coulomb damping is often used in mechanical joints and connections where two parts move relative to each other (Gagnon et al., 2020).

Material (Structural) Damping: Materials themselves exhibit inherent damping properties due to their internal molecular structure. For example, rubber and certain polymers have high damping capacities, meaning they can absorb a significant amount of vibrational energy. Material damping is commonly applied in systems where vibrations need to be suppressed without external dampers (Habibi et al., 2016).

Magnetic Damping: In this case, a conductive material moves through a magnetic field, generating eddy currents that oppose the motion and produce damping. This type of damping is

non-contact and is used in precision instruments where mechanical wear needs to be minimized (Yip & others, 2018).

2.4.4 Vibration Suppression

While damping focuses on dissipating energy, vibration suppression aims to actively or passively reduce the magnitude of vibrations, often before they develop into problematic oscillations. Vibration suppression techniques can be broadly categorized into passive and active methods:

Passive Vibration Suppression: Passive methods do not require external energy or control systems. Instead, they rely on altering the physical properties of the system, such as mass, stiffness, or damping, to reduce vibrations. Examples of passive vibration suppression include:

Tuned Mass Dampers (TMDs): A mass attached to a structure via a spring and damper that is tuned to resonate at the same frequency as the unwanted vibrations, thereby absorbing and dissipating the vibrational energy (Rahimi et al., 2020). TMDs are commonly used in tall buildings and bridges to suppress wind- or earthquake-induced vibrations.

Base Isolation Systems: These systems are used in structures like buildings and machinery, where the base is isolated from the source of vibration through flexible supports or bearings, effectively reducing the transmission of vibrations from the ground or the foundation to the structure (Nobari Azar et al., 2022).

Active Vibration Suppression: Active systems involve sensors and actuators to detect vibrations in real time and apply counteracting forces to cancel out the oscillations. Active control systems are typically more complex and require continuous energy input but can be highly effective in

precision applications such as aerospace or robotics. Active vibration control systems adjust parameters dynamically to counteract disturbances (Nguyen et al., 2020).

Active Magnetic Bearings (AMBs): These systems use electromagnetic forces to support and stabilize rotating shafts without physical contact. By dynamically adjusting the magnetic fields, AMBs can suppress unwanted vibrations in real-time, making them ideal for high-speed machinery like turbines and compressors (Swanepoel, 2020)

2.5 Resonance and the Importance of Damping

Resonance occurs when the frequency of an external force matches the natural frequency of a system, leading to large amplitude oscillations that can result in structural failure or performance degradation. Damping plays a crucial role in preventing resonance by reducing the system's ability to sustain high-amplitude vibrations. The damping ratio is a key parameter that quantifies the effectiveness of damping in a system. A higher damping ratio indicates that the system will return to equilibrium faster after being disturbed, thereby preventing resonant amplification (Rajasekar & Sanjuan, 2016).

Systems with inadequate damping are prone to resonant vibrations, which can lead to severe damage, especially in rotating machinery, bridges, and aerospace structures. By introducing appropriate damping mechanisms, engineers can ensure that the system can absorb and dissipate vibrational energy, thereby reducing the risk of catastrophic failures (Al-Hababi et al., 2020).

2.6 Types of Dampers and Their Working Principles

Dampers are essential devices used to reduce vibrations and oscillations in various mechanical systems. They operate by dissipating kinetic energy, thereby minimizing the amplitude of vibrations. Different types of dampers are employed based on their working principles,

applications, and effectiveness in controlling vibrations. Below, we explore the major types of dampers and their operating principles.

2.6.1 Viscous Dampers

Viscous dampers utilize a fluid to dissipate energy through the viscous shear of the fluid when the damper moves. The resistance offered by the fluid is proportional to the velocity of movement, allowing consistent damping across a range of frequencies.

Working Principle: When a force is applied, the moving part of the damper displaces the fluid through a piston or orifice, generating frictional heat as the fluid flows. The damping force F can be expressed mathematically as:

$$F=c\cdot V \tag{2.1}$$

$$F=\frac{c}{cdot}v \tag{2.2}$$

$$F=c.v \tag{2.3}$$

where c is the damping coefficient

v is the velocity of the moving component (Riaz et al., 2023). This type of damper is commonly used in automotive shock absorbers, where they help absorb shocks from road irregularities, providing a smoother ride (Rajana et al., 2023).

2.6.2 Coulomb Dampers (Friction Dampers)

Coulomb damper's function based on friction between two surfaces in contact. The damping force remains constant and is independent of the velocity of the moving parts, making these dampers suitable for applications requiring a constant resisting force.

Working Principle: When the surfaces in contact begin to slide against each other, friction generates a resistive force that opposes the motion. This frictional force is proportional to the normal load and is described by the equation:

$$F=\mu \cdot NF \tag{2.4}$$

where F is the frictional force,

μ is the coefficient of friction

N is the normal force acting on the surfaces (Lahre et al., 2024). Coulomb dampers are commonly found in applications like seismic isolation systems for buildings and structures, where they help absorb vibrations from earthquakes (Kang et al., 2023).

2.6.3 Spring Dampers

Spring dampers combine the properties of springs and damping elements to provide both restoring force and damping. They can be configured in various ways, such as incorporating viscous fluids or mechanical dampers.

Working Principle: In a spring damper system, the spring provides a restoring force proportional to the displacement, while the damping component absorbs energy. The overall force can be described by:

$$F=KX+CV \tag{2.5}$$

where K is the spring constant

x is the displacement

C is the damping coefficient

V is the velocity (Sorace & Terenzi, 2001). These dampers are frequently used in automotive suspensions and building foundations to provide stability and comfort.

2.7 Criteria for selecting a mechanical damper

2.7.1 Damping Efficiency

The primary criterion for selecting damping materials is their damping efficiency, which refers to the material's ability to dissipate vibrational energy. This is typically quantified using the damping ratio (ζ), a dimensionless measure that indicates the level of damping in relation to critical damping. Higher damping ratios indicate more effective energy dissipation, which is critical in applications where excessive vibrations can lead to failure or reduced performance (Ahmadi Bonakdar et al., 2023) .

Consideration: Engineers should assess the required damping ratio for specific applications, as different materials exhibit varying damping characteristics under different loading conditions. For instance, materials like rubber or viscoelastic polymers are often chosen for their high damping capabilities (Zhou et al., 2016a).

2.7.2 Frequency Response

The frequency response of the damping material is another crucial criterion. Different materials have distinct behaviors at various frequencies, making it essential to select a material that effectively damps vibrations within the operational frequency range of the system.

Consideration: The chosen damping material should ideally exhibit broadband damping, meaning it can efficiently dissipate energy across a wide range of frequencies. This is particularly important in applications like automotive suspensions, where vibrations can arise from multiple sources at varying frequencies (Geweth et al., 2021).

2.7.3 Material Properties

Several intrinsic material properties significantly affect damping performance, including:

Viscoelastic Behaviour: Materials that exhibit viscoelastic properties combine elastic and viscous characteristics, providing effective energy dissipation while allowing for some degree of deformation.

Young's Modulus: The stiffness of the material, represented by Young's modulus, plays a vital role in determining how the material will respond to dynamic loads. Softer materials often provide better damping characteristics, but this must be balanced with the need for structural integrity (Zhou et al., 2016b).

Temperature Sensitivity: The damping performance of materials can change with temperature. Materials that maintain consistent damping characteristics across a range of temperatures are preferred in applications exposed (Krivic & Slavič, 2023)

2.7.4 Mechanical Compatibility

The compatibility of damping materials with the other components of the system is essential. This includes considerations related to:

Adhesion: The ability of the damping material to bond effectively with other materials in the assembly, such as metals or plastics. Poor adhesion can lead to delamination or failure in the damping layer, negating its effectiveness (Treviso et al., 2015).

Dynamic Properties: The damping material must be compatible with the dynamic properties of the system. For instance, materials should not introduce significant additional mass or stiffness

that could negatively impact the overall performance of the system (Poddaeva & Fedosova, 2021).

2.7.6 Environmental Resistance

The ability of the damping material to withstand environmental factors such as humidity, UV exposure, chemicals, and temperature variations is critical, especially for outdoor or industrial applications.

Consideration: Materials should be selected for their durability and resistance to degradation over time, as this directly impacts the longevity and effectiveness of the damping solution. For example, silicone-based materials are often chosen for outdoor applications due to their excellent resistance to UV light and weathering (Williams & Davis, 2020).

2.7.7 Cost and Availability

The cost of damping materials and their availability is a practical consideration in the selection process. While high-performance materials may provide superior damping, budget constraints often necessitate a balance between performance and cost.

Consideration: Engineers should evaluate the total cost of ownership, which includes not just the initial purchase price but also maintenance, replacement, and potential downtime costs associated with the material's performance (Galar et al., 2017).

2.7.8 Design Integration

Finally, the selected damping material must integrate well with the design of the system. This includes considerations related to:

Geometry: The shape and size of the damping material must fit seamlessly within the existing design constraints of the mechanical system.

Assembly Process: The material should be easy to integrate into the manufacturing process, considering factors like ease of installation, handling, and long-term stability (Esmaeilian et al., 2016).

2.8 Design Considerations for Mechanical Dampers

Key factors in designing effective vibration dampers

Designing effective vibration dampers is crucial in engineering to control and mitigate vibrations in various mechanical systems. The performance and effectiveness of these dampers depend on several key factors, which influence their ability to absorb and dissipate energy. Below are the primary considerations in the design of effective vibration dampers.

2.8.1 Comparative Summary of Different Damper Technologies

Table 2.1:Comparative Summary of Different Damper Technologies

Damping Technology	Advantages	Disadvantages	Application Areas
Viscous Dampers	Wide frequency range, effective no other energy dissipation	Performance is affected by temperature changes	Compressors, machinery
Friction Dampers	Simple design, effective for low frequencies	Sensitive to environmental changes, wear issues	Industrial equipment, vehicles
Tuned mass Dampers	Excellent for resonant frequencies	Requires precise tuning, limited by frequency shifts	Buildings, bridges
Rubber/Elastomeric	Cost-effective, good vibration isolation	Performance degradation over time	Machinery mounts, vehicles
Active Dampers	Superior adaptive performance	High complexity and cost, requires power supply	Automotive, aerospace systems
Hybrid Dampers	Combines strengths of multiple technologies	Increased design complexity and cost	Advanced machinery, vehicles

2.9 Case Studies of Vibration Dampers in Compressors

Dampers are essential components in compressors, particularly in semi-hermetic designs, where they mitigate vibrations and enhance performance. Various damper designs have been developed to address the unique challenges posed by compressor operations, including noise, wear, and performance degradation due to vibrations. This review explores the existing damper designs used in compressors, highlighting their principles, applications, and effectiveness.

2.9.1 Viscous Dampers

Viscous dampers use a fluid (usually oil) to absorb and dissipate vibrational energy through viscous shear. They are commonly employed in compressors due to their simplicity and effectiveness.

Application: In semi-hermetic compressors, viscous dampers help control vibrations induced by rotating components and compressor operation. They function by allowing relative motion between components, where the fluid's viscosity resists this motion, converting kinetic energy into thermal energy (Bijanzad, 2017).

Advantages: These dampers provide consistent damping across a wide range of frequencies, making them suitable for varying operational conditions (Saed et al., 2021). Their design can be optimized to match specific compressor frequencies for improved performance.

2.9.2 Friction Dampers

Friction dampers rely on the sliding contact between surfaces to dissipate energy through friction. These designs can be found in various compressor configurations.

Mechanism: In compressors, friction dampers often use pads or shoes that engage with rotating parts. When vibrations occur, the relative motion between the surfaces generate (Jaisee et al., 2021)

Performance: These dampers are effective at reducing low-frequency vibrations, but their performance can be sensitive to changes in temperature and humidity, which may affect the friction characteristics (Shah & Patel, 2021). They are often used in conjunction with other damping technologies for enhanced effectiveness.

2.9.3 Tuned Mass Dampers (TMD)

Tuned Mass Dampers are passive devices designed to reduce resonant vibrations by tuning their mass and stiffness to counteract the vibrational frequencies of the system.

Design: In compressor applications, TMDs are typically mounted on the frame or housing to absorb specific vibration modes. The design involves careful tuning of mass and spring characteristics to match the natural frequency of the compressor (Yang et al., 2022)

Effectiveness: Studies have shown that TMDs can significantly reduce vibrations in compressors, especially during startup and shutdown phases when transient vibrations are prevalent (Williams & Davis, 2020). However, their performance can be frequency-dependent and may require adjustment if the operating conditions change.

2.9.3 Rubber and Elastomeric Dampers

Rubber and elastomeric dampers utilize the viscoelastic properties of materials like rubber to absorb vibrations. These dampers are commonly integrated into the mounting systems of compressors.

Functionality: They work by deforming under load, dissipating vibrational energy as heat. This mechanism is particularly effective in isolating vibrations transmitted to the compressor's casing and surrounding structures (Zhou et al., 2018)

Advantages: Rubber dampers are relatively low-cost and easy to install, providing effective vibration isolation while also reducing noise transmission. However, their performance can degrade over time due to environmental factors like temperature and aging (El Samad et al., 2024).

2.9.4 Active Dampers

Active dampers incorporate sensors and actuators to adaptively respond to changing vibration conditions in real-time.

Technology: These dampers use feedback control systems to adjust damping forces based on the vibration response of the compressor. By actively countering vibrations, they can provide superior performance compared to passive designs (Gavilan et al., 2020).

Application: Active dampers are increasingly being explored in advanced compressor designs, particularly in high-performance or variable-speed applications where vibration characteristics may change rapidly (Jia et al., 2018). However, they are more complex and costlier to implement than traditional passive dampers.

2.9.5 Hybrid Dampers

Hybrid dampers combine different damping technologies to leverage the advantages of each.

Configuration: For instance, a hybrid damper may utilize both viscous and friction damping principles, allowing it to perform well across a range of frequencies and conditions. This design

can enhance the overall performance of compressors by providing both energy absorption and isolation (Shah & Patel, 2021).

Effectiveness: Research indicates that hybrid designs can offer improved vibration reduction in compressors compared to using a single damping mechanism alone. They can be tailored to address specific vibration profiles and operational requirements (Młynarczyk et al., 2021).

2.9.6 Summary of the research gap.

Current vibration dampers for semi hermetic compressors like the spring and rubber dampers, lack systematic optimization techniques to minimize vibration and also oversimplify complex dynamics of semi hermetic compressors leading to inaccurate predictions due to limited simulation studies, insufficient consideration of nonlinear effects like, friction and pressure pulsation is not being adequately accounted for in current design. Furthermore, integration of advanced materials as part of the emerging trends and technologies are not fully explored.

CHAPTER THREE: RESEARCH METHODOLOGY:

This chapter entails the procedure for performing a detailed frequency analysis including identification of critical design parameters, and damper layout development. A mathematical model is then applied to validate the design, demonstrating its ability to suppress vibration.

3.1 Analyzing the current operating condition of the Semi-Hermetic compressor

The first step was to analyze the current operating conditions of the semi hermetic compressor by simulating its working condition on solid works, and variations such as different loads (Refrigerant pressure load generated during refrigerant pumping process, heat loads and vibration loads causing wear and tear), speeds (1450RPM at 50HZ AND 1750 at 60 HZ), and environmental factors (Thermal load generated during compression and expansion process in the compressor generated by compression of refrigerant and heat gained from the surrounding and humidity causing corrosion of parts) were considered.

3.2 Geometric Modeling

A detailed 3D geometric model of the semi-hermetic compressor was created using SolidWorks by following a systematic procedure that ensured accuracy and reproducibility. The process began with defining compressor specifications and setting up the project environment, after which individual components such as the housing, pistons, valves, crankshaft, and connecting rods were modeled using extrusion, revolve, and cut-features based on measured dimensions. These components were then assembled with appropriate mates to achieve correct alignment and motion constraints, model was validated through interference detection and dimensional checks.

3.3 Material Properties

Each component within the SolidWorks model was assigned appropriate material properties. Ensuring precision in the simulation results necessitated the incorporation of accurate material data, including density, Young's modulus, and Poisson's ratio. These crucial material properties played an important role in capturing the realistic structural response of the semi-hermetic compressor components under diverse loading conditions. The accurate representation of material characteristics in the model also contributed significantly to the reliability of the simulation outcomes.

3.4 Mesh Generation

A high-quality mesh was generated for the entire model in preparation for the simulation. Special attention given to refining the mesh in critical areas where significant vibrations are anticipated. These areas include contact points, joints, and interfaces, ensuring that the mesh resolution is optimized for capturing the intricate details of the structural response. The mesh refinement process enhanced the accuracy of the simulation results, particularly in regions that are essential for assessing the vibrational behavior of the semi-hermetic compressor components.

3.5 Boundary Conditions

Boundary conditions were applied to the model. This involved establishing constraints on fixed parts and implementing appropriate loading conditions to accurately simulate the operating environment of the compressor. Factors such as pressure, temperature, and external forces was considered during the application of these boundary conditions. This step is vital for creating a simulation environment that closely mirrors the actual conditions under which the semi-

hermetic compressor operates, providing valuable insights into its performance under various scenarios.

3.6 Dynamic Analysis Setup

The SolidWorks Simulation environment was configured for dynamic analysis. The process included specifying the type of analysis required for dynamic simulations. Which are setting parameters and conditions to conduct a thorough examination of the dynamic behavior of the semi-hermetic compressor components. The configuration step is key in determining the simulation's focus, which is modal analysis, harmonic analysis, which laid the foundation for analyzing system's vibrational characteristics.

3.7 Modal Analysis

Modal analysis was conducted to identify the natural frequencies and mode shapes of the compressor system. This analytical step is essential for gaining insights into the dynamic behavior of the system, revealing key information about its inherent characteristics, by performing modal analysis, potential resonance frequencies and mode shapes was unveiled, contributing to a comprehensive understanding of the semi-hermetic compressor's vibrational properties and aiding in the identification of critical operational points.

3.8 Harmonic Analysis

Harmonic analysis was conducted to simulate the response of the compressor to sinusoidal loading at various frequencies. This analytical process is designed to provide valuable insights into how the compressor reacts to different operational conditions. By exploring the harmonic response, critical frequencies will be identified, contributing to a more thorough understanding of the semi-hermetic compressor's behavior under diverse loading scenarios. This analysis is

instrumental in optimizing the compressor's performance and ensuring its reliability across a range of operational conditions.

3.9 Design components and parameters of the damper for the semi hermetic compressor

A mechanical damper was designed and incorporated to the existing spring mounting on the semi hermetic compressor.

A viscous type of damper was chosen and parameters like stiffness, damping coefficient and viscous fluid properties such as viscosity and density were used.

The damper consists of a piston and cylinder arrangement, where the piston moves through a viscous fluid creating a resistant force that opposes the motion generated during vibration. The resistant force generated by the viscous fluid is proportional to the velocity of the piston which slows down motion and suppresses vibration.

Simulation on solid works was run to generate amplitudes at different frequencies and a graph of amplitudes against different frequencies was plotted to point out areas of improvement in the amplitude of vibration.

3.10 Layout of the mechanical damper

The mechanical damper is a viscous type, with a linear type of motion, the layout took into consideration space limitation and compressor weight, piston and cylinder were designed considering factors like diameter and stroke. A suitable viscous fluid was selected, viscosity, density and stability were fluid properties considered during selection. Finally seals and gaskets were designed to solve fluid leakage.

Determining the damping force

$$F_d = \text{CV} \tag{3.1}$$

Where c is the damping coefficient

And V is the velocity

But C = 2. ℑ.m.w_n

ℑ is the damping ratio

M is the mass of the object being damped

w_n is the natural frequency

Also,

V = 2.π.f.A

V is the velocity

F is the frequency of vibration

A is the amplitude of vibration

Shaft diameter (d) is calculated using the following equation

$$\text{d} = \sqrt{(4F_d . \frac{SF}{\pi\sigma})} \tag{3.2}$$

Where F_d is damping force

σ material yield strength

SF factor of safety.

Also, pressure P = p g h

Where p is fluid density

g acceleration due to gravity

h is height of the fluid column

but pressure P = $\frac{F_d}{A}$

m.$\ddot{X}$ from Newton's law of motion F = ma

c$\dot{X}$ is the fluid damping force, where c is the damping coefficient

kx being spring force from F =kx where k is spring stiffness and x is the spring displacement

Divide all through my m

$$\ddot{X}(t) + \frac{C\dot{X}}{m} + \frac{kx}{m} = \frac{F0}{m}\sin(wt) \tag{3.5}$$

$f_0 = \frac{F_0}{m}$ $w_n = \sqrt{\frac{k}{m}}$ which is the natural frequency of the system.

$\epsilon = \frac{c}{2\sqrt{km}}$ Damping ratio

The forced response of a damped system has the same frequency as the driving force but with a different amplitude and phase. Therefore

$$X_P(t) = x.\sin(wt+\theta) \tag{3.6}$$

Where X is the amplitude

θ is the phase angel

This is then simplified to an equation for an over damped system below

$$X = \frac{f_0}{\sqrt{(w_n{}^2 - w^2)^2 + (2.\epsilon.w_n.w)^2}} \tag{3.7}$$

The amplitude of the steady state vibrations depends on the driving frequency.

When $r = \frac{w}{wn}$

The above equation can be written as

$$\frac{xw_n{}^2}{fo} = \frac{1}{\sqrt{(1-r^2)^2 + (2.\epsilon.r)^2}} \tag{3.8}$$

Where r is frequency ratio

X is the amplitude

The above equation is used to generate the figures below at a damping ratio of 0.1,0.2,0.4,0.8 and 1

A Values at different damping ratios ∈ are amplitudes generated by applying a frequency ratio of 0.1 up to 2 in the above formula.

Table 3.1 the values above are plotted as Amplitude versus the frequency ratio for different damping ratio ϵ

Table 3.1:Amplitude versus frequency ratio for different damping ratio E

R1	A At ∈=0.1	r2	A At ∈ =0.2	r3	A At ∈ =0.4	r4	A At ∈ = 0.8	r5	A At ∈ = 1
0.1	1	0.1	1	0.1	1	0.1	1	0.1	1
0.2	1	0.2	1	0.2	1	0.2	1	0.2	1
0.6	1.5	0.6	1.2	0.6	1.1	0.6	1	0.6	0.9
1	5	1	2.5	1	1.5	1	0.9	1	0.7
1.2	2	1.2	1.4	1.2	1.1	1.2	0.8	1.2	0.6
1.5	0.7	1.5	0.6	1.5	0.5	1.5	0.6	1.5	0.5
2	0.3	2	0.3	2	0.3	2	0.3	2	0.3

AMPLITUDE

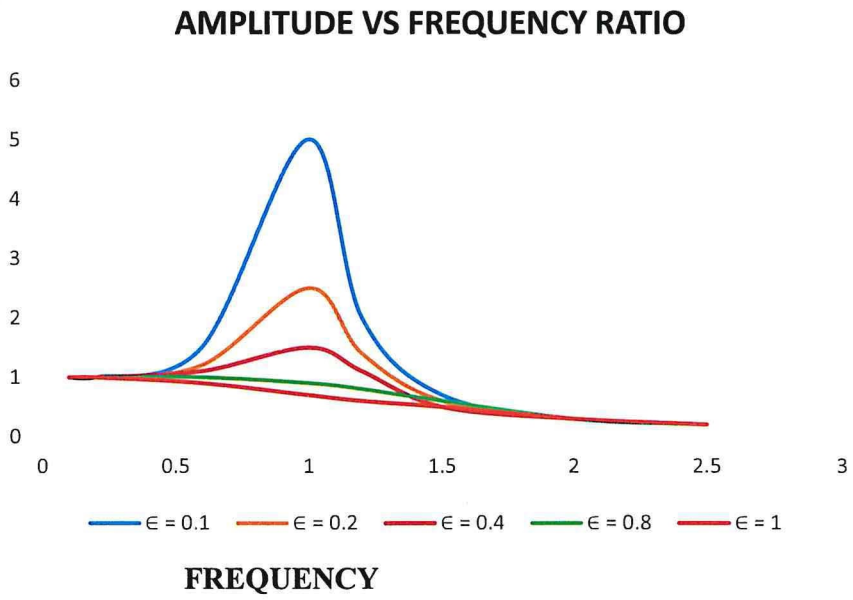


Figure 3.2: Reduction in amplitude of vibration with increase in damping ratio

$\in$ = Damping ratio

From the graph its clearly seen that amplitude is maximum when frequency ratio is at 1

The amplitude reduces with increase in damping ratio that is the frequency for which the maximum amplitude is obtained moves away from the natural frequency until there is no peak.

The maximum amplitude is obtained when r $=\sqrt{2(1-2\in^2)}$ when $0\leq\in<\frac{1}{\sqrt{2}}$ and amplitude is not at peak when $\in=\frac{1}{\sqrt{2}}$.

This mathematical model was therefore used to design a Rheological silicon oil damper to suppress vibration in the semi hermetic compressor.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Introduction

This section focused on the analysis of the Current Operating Condition of The Semi-Hermetic Compressor at Carrefour from Solid Works Simulation.

3D Model of semi-Hermetic compressor



Figure 4.1: A 3D model of the semi-hermetic

The above was designed With Parameters as Shown in Table 4.1 Spring Parameters

Table 4.1:Spring Parameters

Spring parameters	Values
Spring wire diameter	11mm
Spring coil diameter	140mm
Number of coils	7
Spring constant k	156960N/m
Spring rated deflection	25
Tensile strength:	1.51658e+08 N/m^2
Compressive strength	5.72165e+08 N/m^2
Elastic modulus	6.61781e+10 N/m^2
Poisson's ratio	0.27

Boundary conditions which define how the compressor interacts with its surroundings, were considered examples, strain temperature and thermal loads.

Meshing was done to enable the geometry to be divided into small, simple elements to accurately represent the physical behaviour of the model under various conditions. Meshing helps define and apply boundary conditions accurately.

Table 4.2: Study properties and boundary conditions

Study properties and boundary conditions	Values
Analysis type	Linear dynamic analysis (Response Spectrum Analysis)
Mesh type	Solid Mesh
Upper Bound Frequency	50
Thermal option	Include temperature loads
Zero-strain temperature	298 Kelvin

Modal analysis, modal analysis was carried out to determine the natural frequencies and mode shapes of the compressor structure. Dominant vibration modes that contribute to the overall vibration behavior of the compressor was identified and five nodes of frequency was considered.

Name	Type	Min	Max
Amplitude1	AMPRES: Resultant Amplitude Plot for Mode Shape: 1(Value = 1.88163 Hz)	0.000e+00 Node: 82441	9.215e-02 Node: 29077

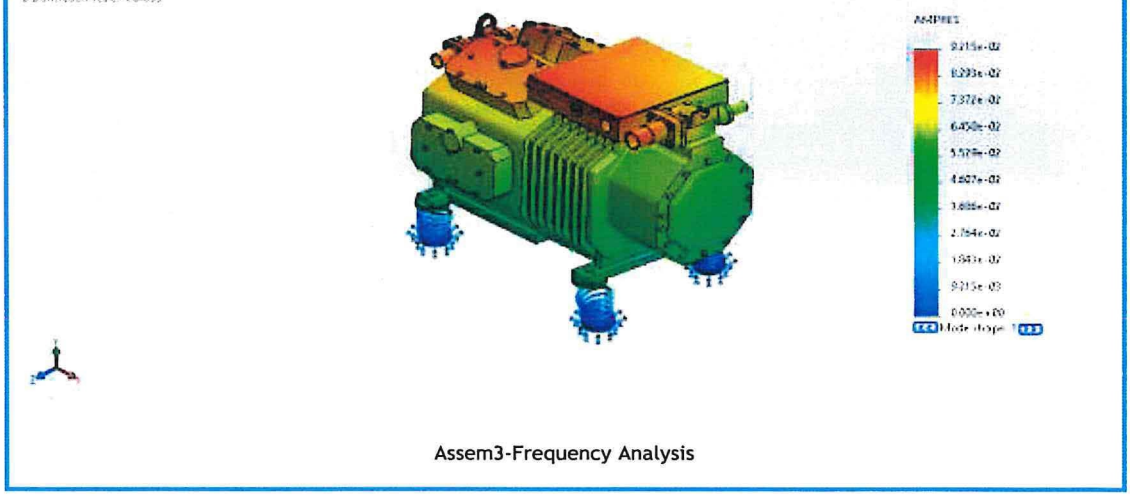
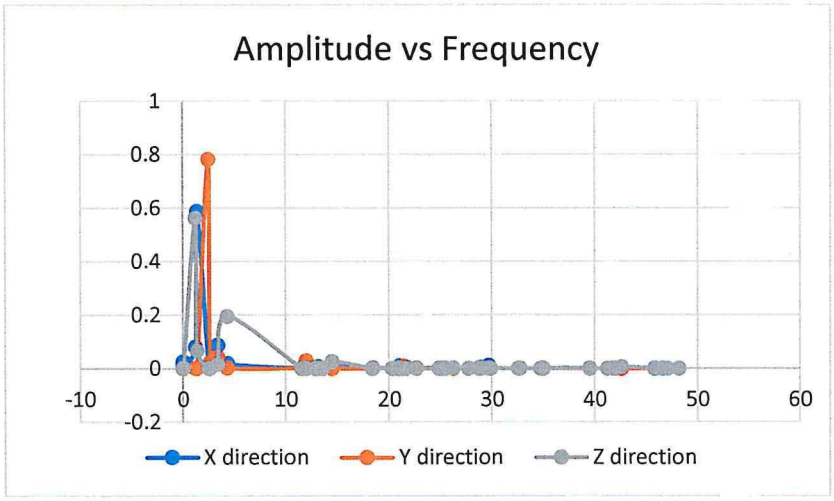


Figure 4. 2: semi hermetic compressor subjected toa range of vibration frequencies

A range of frequency values was generated with corresponding amplitude replicating the vibration frequency on the semi hermetic compressor on site (Table 4.3 refer to appendices).

A graph was plotted detailing the vibration frequency variation against amplitude.

Amplitude



Frequency

Figure 4.3: A Semi hermetic compressor vibration behavior when mounted on springs only

As seen from the graph vibration frequency is highest in Y-direction at amplitude peak of 0.782 which then drops gradually to zero. In the X-direction amplitude is highest at 0.58574 which then drops to zero. In the Z- direction amplitude is highest at 0,56202 at a frequency of 1.2003 Hz, which then gradually drops to zero and rises again up to 0.19505.

This explains the compressor vibration behaviour at the compressor start up and shut down, at start up the refrigerant rushes into the compressor to raise pressure to a minimum of 30psi on the low-pressure side, at this point the refrigerant pressure coupled with compressor torque causes a large unbalanced force which result in severe compressor vibration larger than the amplitude of steady state compressor vibration. This is seen at a frequency of 2 to 3.2Hz with

amplitude of 0.391Hz on the Xdirection,$8.97x1010^2$ in the Y direction, and 0.4467 in the z direction.

During compressor shutdown, the compressor decelerates to zero, the rapid deceleration causes the compressor to undergo angular acceleration resulting in a torsional kick to the compressor body as seen at a frequency of 0.00079401Hz, Compressors operate by compressing fluid (e.g., refrigerant or air), and the interaction between the fluid and compressor structure contributes to vibration. Flow-induced vibration, pulsations, and pressure fluctuations within the compressor can excite structural modes and lead to vibration.

one of the major contributors to the spikes in amplitude on the graph above is Resonance which occurs when the natural frequency of the compressor system matches an external excitation frequency. External factors such as motor vibration, fluid flow, or structural resonance can also induce vibration in the compressor. Resonance amplifies vibration levels and lead to excessive wear and fatigue in compressor components.

Besides the above analysis, operating conditions such as speed, load, and temperature can impact compressor vibration. High-speed operation, overloading, and operating near resonance frequencies increases vibration levels. Additionally, variations in operating conditions over time affects vibration characteristics.

Furthermore, the dynamic behaviour of the compressor rotor, including unbalanced forces, critical speeds, can influence vibration levels. Rotor dynamics issues, such as shaft bending, can lead to self-excited vibration and rotor instability.

4.2 Mechanical damper design components and parameters.

The damper components are a stainless-steel cylinder of inside diameter 110mm, a shaft of diameter 6mm, a piston diameter 110mm and stroke 20mm) and a seal. the damper is a viscous type filled with a rheological fluid damping ratio was used in the range of (0.1-1).

Table 4.3: Rheological fluid parameters

Rheological fluid parameters	**Values**
Density	920 kg/m^3
Specific heat	4.18J/KgK
Thermal conductivity	0.6W/mK
Viscosity	Herschel-Builkey model
Consistency coefficient	0.61Pa
Yield stress	262000000Pa
Power-low index	1

Compressor natural Frequency (21.2mm), spring stiffness (156960N/m)

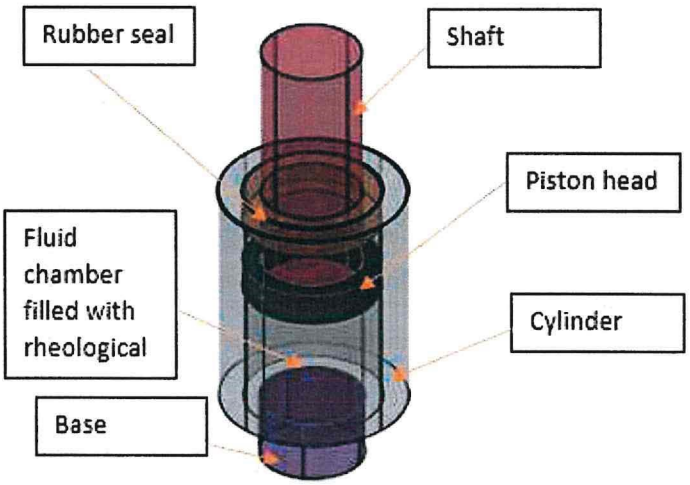


Figure 4.4:Rheological damper layout

From the equation (3.2), shaft diameter is 6mm, piston head radius 55mm and cylinder wall thickness is

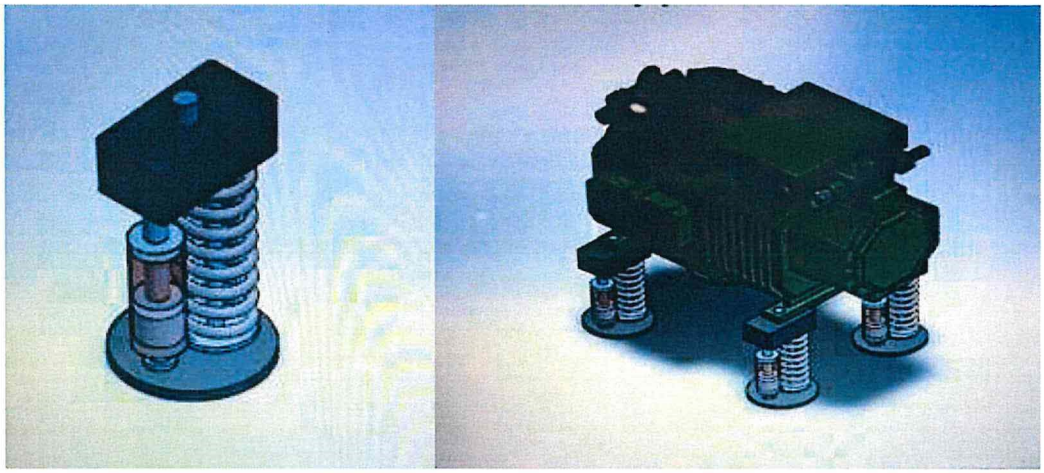


Figure 4. 5: The 3D model of a spring incorporated with a damper

The damper is designed with a stainless-steel housing, and a height of 188mm, filled with a rheological fluid. Rheological silicon oil properties make them valuable in scenarios where precise control over viscosity is required. It can maintain their viscosity across a wide range of temperatures, ensuring consistent damping performance even in varying environmental conditions (Li et al., 2019) .



Figure 4.6: Semi-hermetic compressor under study

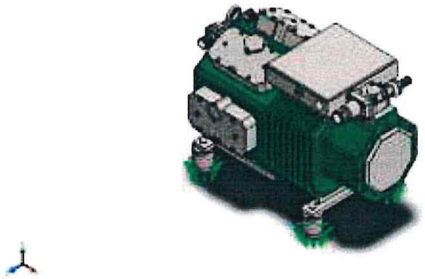


Figure 4.7: 3D Model of compressor on site

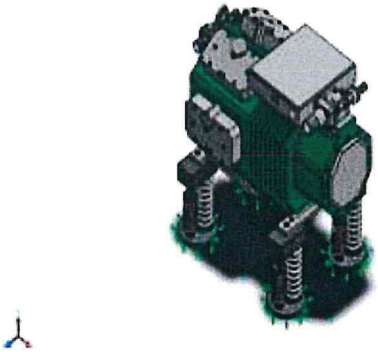


Figure 4.8: 3D model of the compressor on introducing the damper

Table 4.4: boundary conditions used in simulation

Parameter and boundary condition	Values
Analysis type	Linear dynamic analysis (Modal Time History)
Mesh type	Solid Mesh
Upper Bound Frequency	50
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin

Table 4.5: Material properties and parameters used during simulation

Model Reference	Properties
	Name: Cast Alloy Steel Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 2.41275e+08 N/m^2 Tensile strength: 4.48083e+08 N/m^2 Elastic modulus: 1.9e+11 N/m^2 Poisson's ratio: 0.26 Mass density: 7,300 kg/m^3 Shear modulus: 7.8e+10 N/m^2 Thermal expansion coefficient: 1.5e-05 /Kelvin
	Name: Spring and damper Model type: Linear Elastic Isotropic Default failure criterion: Unknown Yield strength: 9.23737e+06 N/m^2 Tensile strength: 1.37871e+07 N/m^2 Elastic modulus: 6.1e+06 N/m^2 Poisson's ratio: 0.49 Mass density: 1,000 kg/m^3 Shear modulus: 2.9e+06 N/m^2 Thermal expansion coefficient: 0.00067 /Kelvin

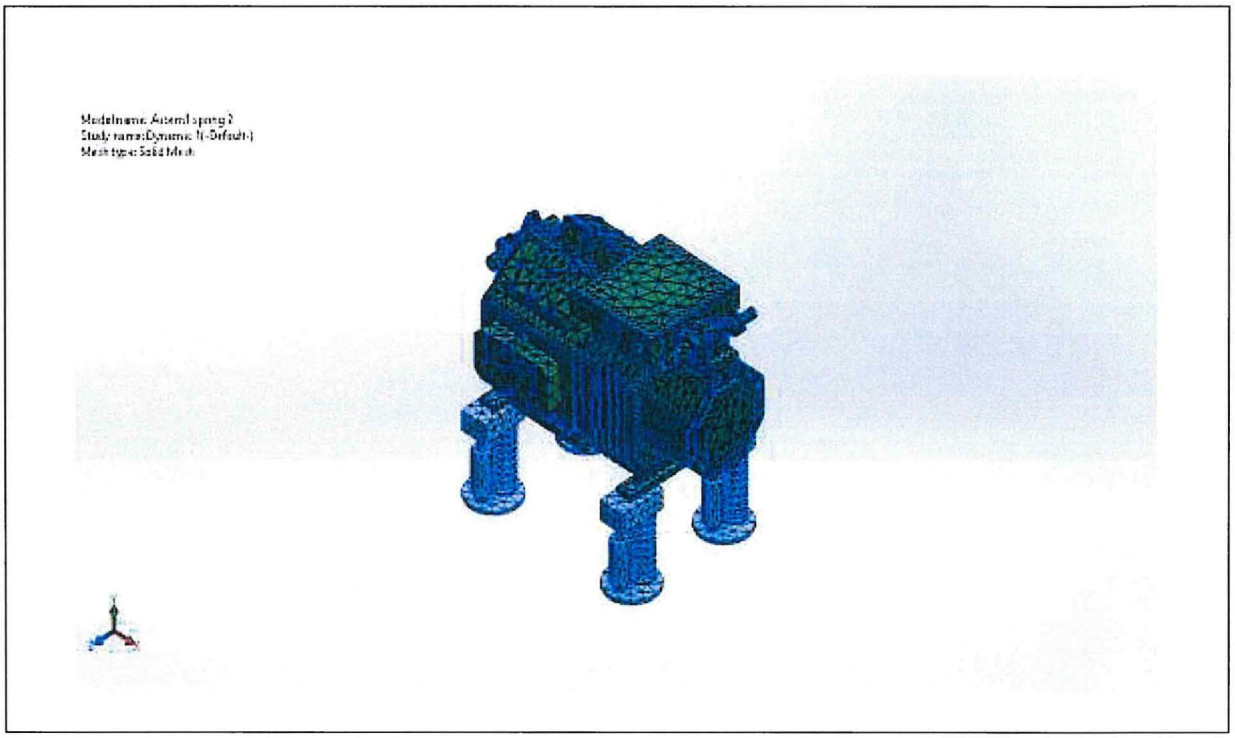


Figure 4.9: Meshing was done for numerical analysis and simulation

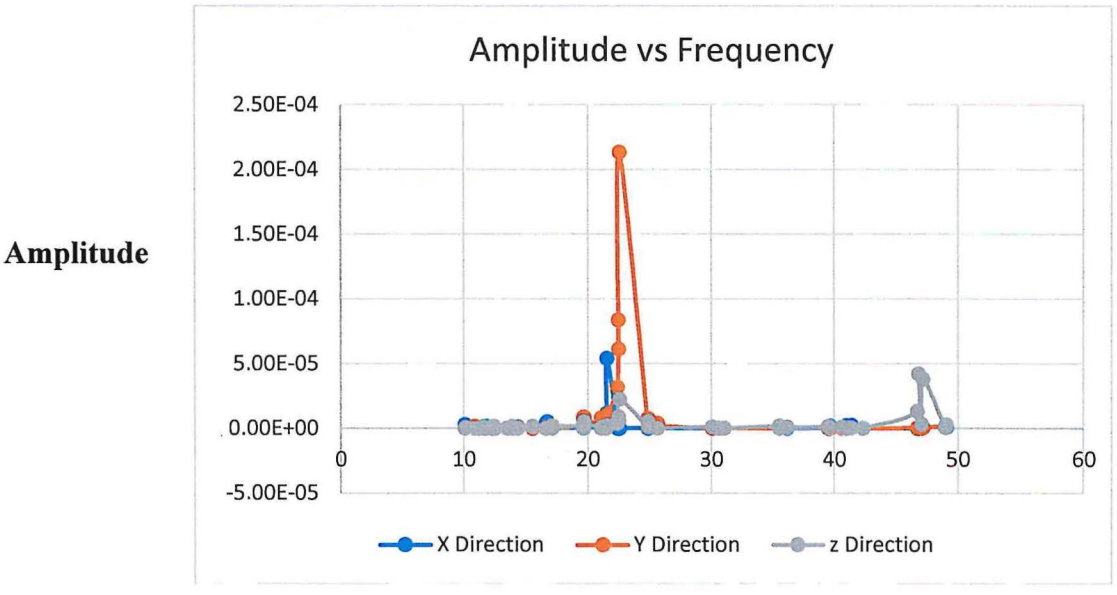


Figure 4.10: Amplitude versus frequency

The amplitude was generated at frequency of 10Hz to 50Hz.As seen from the graph the highest amplitude was 2.1x 10^{-4} ,in the Y plane which is almost negligible and far lower than the amplitude of the spring compressor mounting alone. In the X plane the highest amplitude is at 5.4 x10^{-5} and in the z direction the amplitude of vibration is near zero and it is at this plane that vibration is more dominant.

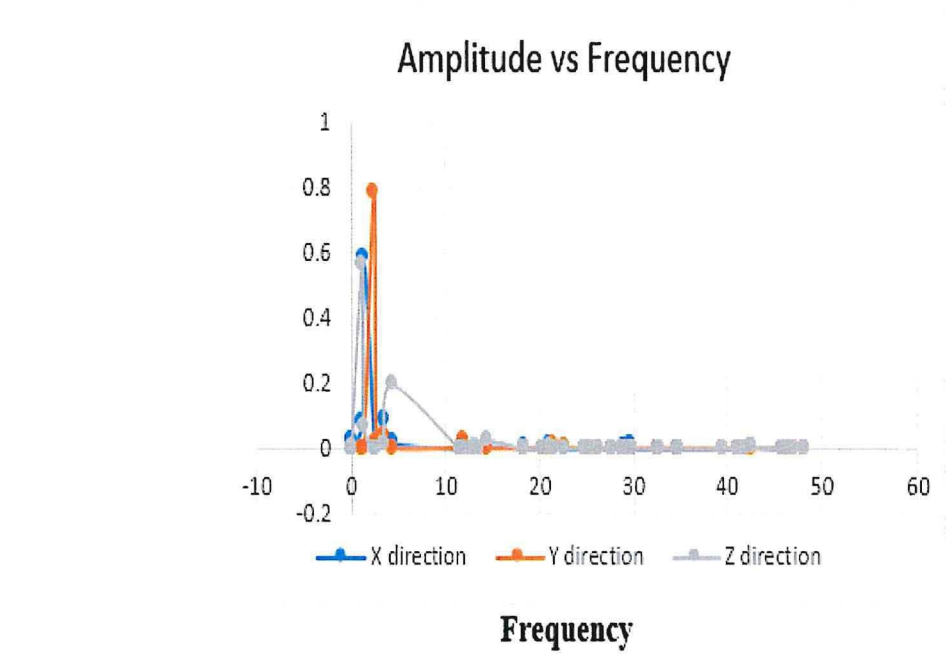


Figure 4. 11: Amplitude range with spring mount

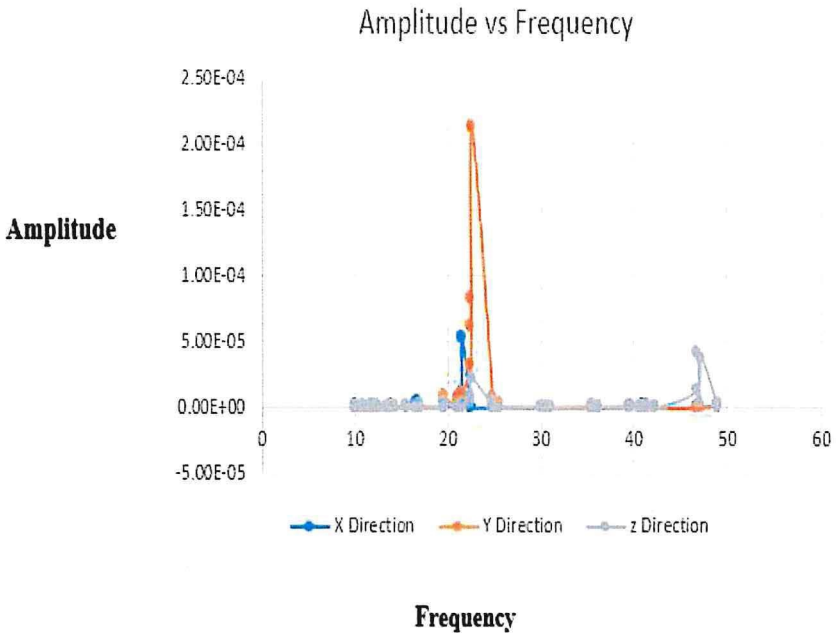


Figure 4. 12Amplitude versus frequency for a spring damper system

The graphs compare amplitude–frequency responses in three axes (X, Y, Z) for the semi-hermetic compressor, first in its current state and then after adding a mechanical damper, the shift in the curves shows damping effects with reduced amplitude peaks and a smoother, safer response across the spectrum.

Before adding the damper (graph 4.11)

Peaks appear in all axes, with the X direction showing the highest amplitude of 0.8mm. This is a result of torsional kick during compressor start up and shut down, coupled with resonance High amplitude at resonance raises risks of fatigue, mount cracking, seal wear, and noise, especially if this frequency coincides with typical operating harmonics. (Example, rotational, blade-pass).

After adding the damper (graph 4.12).

Peak suppression, amplitudes are consistently lower across frequencies with highest amplitude at 2.14x10 -4 mm, resonance peak is significantly reduced. This is the expected effect of added damping; energy dissipation lowers the vibration amplitudes

4.3 Validation of the effectiveness of the damper

Rheological fluids exhibit damping ratio of 0 to 1

The frequencies with their corresponding amplitudes are inserted in the mathematic formula below and a table of values generated and then plotted on a graph

$$\frac{xw_n{}^2}{fo} = \frac{1}{\sqrt{(1-r^2)^2+(2.\epsilon.r)^2}} \tag{4.1}$$

$fo = \frac{Fo}{m}$ Applied force to mass ratio

fo =10

X = amplitude of vibration

W = driving frequency

$w_n = \sqrt{\frac{k}{m}}$ natural frequency of the system

K=156960N/m

M=350kg

Where k is the spring constant and m is the mass mounted on the spring

r =$\frac{w}{wn}$

ϵ = damping ratio

Table 4.6: Amplitudes generated at varying frequency ratios and amplitudes using a mathematical model.

Frequency w	Frequency Ratio (r)	Amplitude ($\epsilon = 0.1$)	Amplitude ($\epsilon = 0.2$)	Amplitude ($\epsilon = 0.4$)	Amplitude ($\epsilon = 0.8$)	Amplitude Ratio (ϵ=1)
10.107	0.479	0.028939	0.028301	0.026112	0.020676	0.018279
11.115	0.527	0.030787	0.029867	0.02687	0.02024	0.017587
12.336	0.585	0.033636	0.032187	0.027836	0.019643	0.016742
13.505	0.64	0.037198	0.034921	0.028755	0.019011	0.015942
14.193	0.673	0.039888	0.036856	0.029276	0.018607	0.015467
15.536	0.736	0.046683	0.041254	0.030117	0.017784	0.014575
16.604	0.787	0.054557	0.045494	0.030544	0.017083	0.013876
17.121	0.811	0.05933	0.047652	0.030634	0.016746	0.013555
19.645	0.931	0.098148	0.056816	0.029701	0.015027	0.012038
21.064	0.998	0.112562	0.05629	0.028146	0.014074	0.011258
22.393	1.061	0.09111	0.050769	0.026189	0.013202	0.010571
24.860	1.178	0.049535	0.036827	0.022052	0.011679	0.009411
25.608	1.214	0.042209	0.033124	0.020796	0.01124	0.009083
30.81	1.46	0.019229	0.017647	0.013818	0.008658	0.007175
31.031	1.471	0.018719	0.017231	0.013578	0.00856	0.007103
35.521	1.683	0.012061	0.01151	0.009883	0.006899	0.005863
36.186	1.715	0.0114	0.010915	0.009454	0.006685	0.005701
39.581	1.876	0.008822	0.008548	0.007663	0.005735	0.004973
40.627	1.925	0.008222	0.007989	0.007218	0.005481	0.004775
41.133	1.949	0.007953	0.007735	0.007013	0.005364	0.004683
42.359	2.008	0.007346	0.007164	0.006548	0.005088	0.004465
46.740	2.215	0.005717	0.005611	0.005238	0.004261	0.003804
47.078	2.231	0.005616	0.005512	0.005155	0.004204	0.00376
49.023	2.323	0.005083	0.005	0.004708	0.003903	0.003512

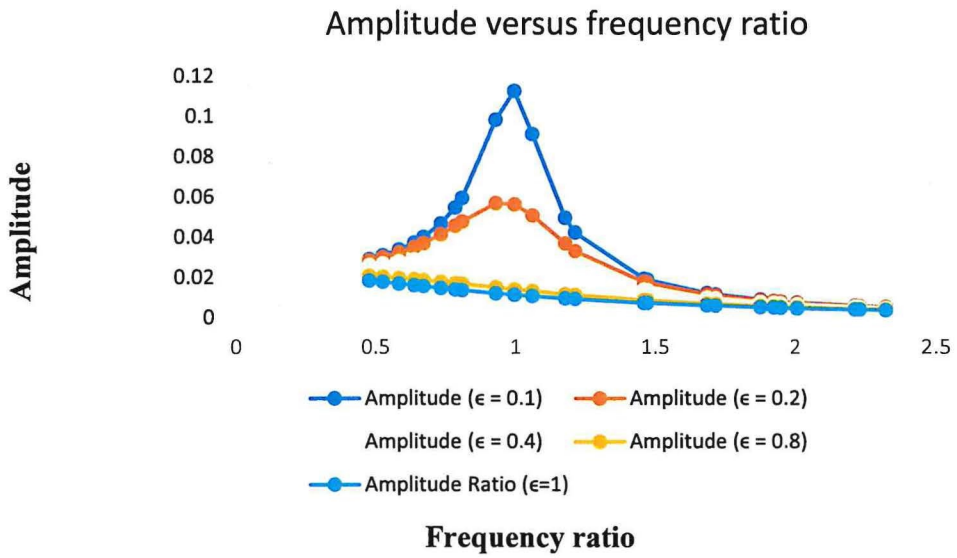


Figure 4.13: Amplitude versus frequency Ratio

The amplitude of vibration is suppressed by increasing the damping ratio.

At damping ratio of 0.1 the highest peak is recorded, indicating minimal damping and large amplitude, also because of resonance at frequency ratio of 1 natural frequency matches excitation/driving frequency. As damping increases, the frequency for which maximum amplitude is obtained shifts away from natural frequency until there is no peak, the system is heavily damped and vibration is suppressed. The lowest amplitude is recorded at damping ratio of 0.8, indicating significant damping, increasing damping suppresses vibration which therefore proves the effectiveness of the damper.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The vibration analysis revealed distinct frequency patterns corresponding to various operating conditions of the semi-hermetic compressor. These frequencies indicated various vibration amplitudes levels and resonance zones, calling for mitigation to enhance compressor stability and longevity.

The study identified key mechanical and operational components including mounting structures, compressor mass, and damping characteristics as significant contributors to vibration behaviour. Ensuring these parameters are optimized was key to achieving effective vibration control.

A mechanical damper layout was successfully designed to target critical vibration frequencies. The design combines isolating and energy-dissipating features, providing better vibration suppression without interfering with the operation of the compressor.

The mathematical model confirmed the effectiveness of the damper in suppressing vibration amplitudes. Simulations demonstrated that the proposed design significantly improved dynamic response and reduced system resonance, validating the effectiveness of the damper in suppressing vibration.

5.2 Recommendations

Based on the findings of this research, the following recommendations are made to improve vibration suppression in semi-hermetic compressors:

The designed mechanical damper should be integrated into semi-hermetic compressors to effectively reduce vibration amplitudes. Further testing of damper can be done under different operational conditions to verify its adaptability and performance.

Future designs should explore advanced damping materials, such as viscoelastic polymers or composite materials, to enhance vibration absorption and durability. The material properties, including elasticity and resistance to fatigue, should be optimized for long-term reliability.

Further refinement of the damper's structure through computational simulations and experimental testing is recommended to improve efficiency. Adjustments to the damping ratio and stiffness should be considered to ensure minimal energy loss while maintaining vibration suppression.

Future research should explore hybrid damping solutions that integrate passive and active damping mechanisms for enhanced vibration suppression. Smart materials and real-time control systems could be incorporated to dynamically adjust damping performance based on operational conditions.

Routine vibration analysis should be conducted to assess the performance of the mechanical damper over time. Predictive maintenance strategies, such as condition-based monitoring, should be employed to prevent unexpected failures and optimize compressor performance.

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APPENDICES

Appendix 1: Vibration amplitude at various frequencies generated by mounted springs

Frequency (Hertz)	X direction	Y direction	Z direction
0.01251	0.0252	2.39E-08	0.00246
0.01258	0.01466	1.67E-08	0.00145
0.01273	0.01817	1.32E-08	0.00179
0.02423	0.00463	3.24E-08	0.00045
0.02986	0.00211	5.11E-09	0.0002
0.03003	0.00207	6.32E-09	0.0002
0.03036	0.00209	3.33E-09	0.0002
0.05778	0.0005	7.33E-09	4.90E-05
1.2003	0.0797	0.00062	0.56202
1.3623	0.58754	0.00127	0.06617
2.4734	0.00999	0.78193	0.00063
2.642	8.06E-09	0.0219	0.00026
3.3895	0.08688	0.0429	0.0151
4.3045	0.01878	0.00195	0.19505
11.535	0.00088	0.00183	0.00028
11.78	0.00078	0.00448	0.00191
11.976	0.002	0.02944	8.86E-05
12.839	0.00039	0.00056	9.53E-05
12.877	0.00035	0.00158	0.00195
13.152	0.00036	0.00031	6.81E-06
13.158	0.00691	0.00494	0.00216
13.597	0.00022	3.27E-06	0.00083
14.507	0.00853	3.45E-05	0.02594
18.371	0.00034	8.96E-05	4.88E-05
18.405	0.00112	0.00043	9.67E-05
18.433	0.00273	0.00084	0.00033
20.296	0.00033	1.50E-06	0.00014
20.416	1.88E-05	6.75E-06	2.18E-06

21.019	0.00912	9.13E-06	0.00312
21.254	4.62E-06	0.00058	4.41E-05
21.422	0.00016	0.00944	0.00015
21.655	0.00429	0.00012	0.00147
22.66	0.00065	0.00266	3.12E-06
24.836	0.00131	0.00065	4.80E-05
24.873	0.00067	0.00047	5.41E-05
25.001	0.0008	0.00018	7.14E-05
25.082	0.00114	0.00035	0.00038
25.236	1.51E-06	7.40E-06	1.81E-05
25.336	5.92E-06	9.38E-06	9.73E-05
25.395	2.09E-05	0.00128	0.00189
26.21	0.00039	2.06E-06	0.00178
27.701	7.41E-06	3.80E-05	1.70E-07
27.747	3.17E-06	0.00075	9.14E-07
27.754	4.35E-05	0.00116	1.31E-05
28.752	0.00043	1.06E-05	0.00012
28.968	0.00349	2.66E-05	0.00044
29.717	0.01068	0.00022	0.00165
29.787	1.53E-05	6.21E-05	5.44E-05

Appendix 2: Amplitude generated by subjecting the semi-hermetic compressor to varying frequencies of vibration at different damping ratios

Frequency (Hertz)	X direction	Y direction	Z direction
10.107	2.4462e-07	7.4752e-09	5.6347e-08
10.107	1.894e-07	6.2324e-09	4.2849e-08
10.107	2.6641e-06	8.9621e-08	6.126e-07
10.167	3.7116e-09	9.5401e-08	4.75e-07
10.168	3.9078e-09	9.0826e-08	4.7237e-07
10.168	2.5215e-09	4.4762e-08	2.1675e-07
10.169	3.6573e-09	1.1491e-07	5.8616e-07
10.883	2.189e-08	8.8878e-07	2.9248e-08
10.883	6.5067e-09	2.7703e-07	9.0259e-09
10.884	4.1297e-08	1.6154e-06	4.9906e-08
10.884	2.671e-08	9.9082e-07	3.0395e-08
11.115	1.713e-08	3.3359e-08	2.2649e-08
11.116	1.0425e-08	2.1249e-08	1.3727e-08
11.116	1.3589e-09	3.3512e-09	1.5882e-09
11.116	7.174e-10	1.4597e-09	1.2015e-09
11.258	5.7866e-07	6.3095e-07	4.6343e-08
11.258	9.1252e-09	1.0146e-08	5.2534e-10
11.258	1.1585e-07	1.2623e-07	6.4374e-09
11.258	5.7454e-07	6.231e-07	4.0811e-08
11.612	5.2812e-07	9.6955e-10	4.0824e-07
11.612	9.4692e-08	3.0363e-11	5.8869e-08
11.613	2.5337e-07	3.4127e-10	1.8051e-07
11.613	1.3179e-06	1.6271e-09	9.2956e-07
11.744	1.194e-07	8.3339e-08	3.0182e-08
11.744	2.5948e-08	1.8863e-08	7.7865e-09
11.744	1.2927e-07	9.2733e-08	3.6967e-08
11.744	1.1975e-07	8.4758e-08	3.3336e-08
11.809	2.3735e-07	3.5932e-08	2.1488e-09
11.809	4.7016e-08	7.0925e-09	8.335e-10

11.809	6.05e-11	3.0361e-12	6.6958e-12
11.809	1.4607e-06	2.2356e-07	2.5823e-08
12.336	1.5953e-07	2.8462e-07	1.458e-06
12.337	1.4372e-07	2.5542e-07	1.3097e-06
12.339	9.7877e-08	1.9299e-07	1.1121e-06
12.339	1.3394e-07	2.2967e-07	1.2631e-06
12.409	1.038e-08	3.1354e-07	2.0935e-12
12.409	3.1846e-08	9.3937e-07	1.0839e-10
12.411	1.3721e-08	4.281e-07	6.6049e-10
12.411	4.9699e-08	1.4161e-06	1.852e-09
12.538	1.445e-09	9.5469e-08	2.2831e-07
12.539	4.8567e-10	2.1746e-08	5.4878e-08
12.539	2.4168e-10	4.6028e-08	1.0983e-07
12.539	2.68e-10	1.5071e-08	3.2022e-08
13.504	1.1866e-07	2.7367e-07	3.6249e-08
13.505	8.1713e-08	1.8153e-07	2.4479e-08
13.505	3.864e-08	9.2047e-08	1.3598e-08
13.505	1.5842e-07	3.6149e-07	4.9822e-08
13.681	2.0112e-08	1.009e-07	1.3932e-07
13.681	2.1074e-08	1.119e-07	1.4926e-07
13.681	1.2551e-08	6.8482e-08	9.3382e-08
13.681	7.1749e-08	3.3305e-07	4.4143e-07
13.88	6.7406e-10	8.4895e-10	2.1706e-09
13.881	1.3603e-06	8.5423e-07	1.1508e-06
13.881	1.5897e-08	1.0705e-08	1.206e-08
13.881	7.7575e-07	4.8271e-07	6.5862e-07
14.193	6.4458e-09	2.853e-08	4.679e-09
14.193	6.9768e-09	3.2885e-08	5.0011e-09
14.193	5.0586e-11	2.9407e-10	4.4487e-11
14.193	6.7828e-11	3.2564e-10	7.0164e-11
14.35	7.3708e-08	3.9381e-08	2.2253e-08

14.35	1.678e-07	9.2781e-08	5.991e-08
14.351	6.3691e-08	3.5031e-08	1.9134e-08
14.351	1.124e-06	6.0328e-07	3.6107e-07
15.536	3.5793e-07	7.0576e-09	1.0607e-06
15.537	4.1789e-07	4.9772e-09	1.2783e-06
15.54	4.3326e-07	1.064e-08	1.3123e-06
15.544	5.0065e-07	9.5805e-09	1.4497e-06
16.604	3.1606e-06	5.3407e-07	5.6672e-08
16.715	3.5198e-06	4.6046e-07	4.5779e-08
16.738	2.2665e-06	3.5632e-07	7.0103e-08
16.743	4.9891e-06	5.0031e-07	8.1371e-08
17.12	2.8411e-08	7.5602e-08	2.1175e-06
17.121	3.2787e-13	7.8406e-11	1.138e-10
17.122	1.014e-08	2.144e-08	5.8029e-07
17.122	4.143e-08	6.1477e-08	1.7564e-06
19.645	5.9159e-07	2.0513e-06	1.2292e-06
19.651	2.3709e-07	9.9843e-07	6.1429e-07
19.654	1.794e-06	9.0149e-06	5.3477e-06
19.666	1.341e-06	7.1546e-06	4.239e-06
21.064	4.8884e-08	1.5646e-06	1.0975e-07
21.066	9.7906e-08	1.9761e-06	1.4071e-07
21.067	1.935e-08	3.7782e-06	1.6885e-07
21.068	1.0983e-07	8.2747e-06	5.1622e-07
21.408	7.8352e-06	2.1496e-07	6.7867e-08
21.471	2.5917e-06	3.3136e-07	5.538e-08
21.49	1.1547e-05	6.0197e-07	1.3739e-07
21.527	5.4044e-05	1.084e-05	2.1613e-06
22.393	4.1489e-08	3.1814e-05	3.4107e-06
22.453	1.7795e-08	8.3891e-05	9.0645e-06
22.486	3.3986e-07	6.1287e-05	6.3234e-06
22.564	5.2293e-09	0.00021366	2.2576e-05
24.86	9.7877e-08	1.2235e-06	8.8625e-07

24.862	5.0075e-07	6.0194e-06	4.4201e-06
24.864	6.1619e-07	7.6877e-06	5.2726e-06
24.876	6.4592e-07	7.6552e-06	5.1703e-06
25.608	2.3211e-09	1.9169e-06	3.41e-08
25.609	1.0683e-09	4.0673e-06	5.9276e-08
25.61	2.3886e-10	1.0161e-06	1.7973e-08
25.611	7.5173e-10	1.7555e-06	3.4237e-08
30.081	1.1702e-10	6.4342e-08	1.0536e-06
30.085	1.097e-09	4.4374e-08	6.8675e-07
30.085	1.0681e-10	4.3623e-08	7.3604e-07
30.091	7.5357e-12	5.418e-08	7.7759e-07
30.567	4.4442e-09	3.5416e-09	4.8858e-08
30.568	2.1791e-08	3.3901e-08	3.1522e-07
30.568	3.2384e-08	2.2309e-08	3.4131e-07
30.571	3.3789e-08	3.8031e-08	4.1308e-07
30.728	2.6273e-08	2.6651e-08	1.0903e-08
30.803	5.1189e-08	6.079e-08	5.0201e-09
31.031	1.2058e-07	3.3248e-08	5.6494e-09
31.051	1.6114e-07	8.0145e-12	7.0979e-09
35.521	3.1178e-07	6.5028e-11	1.7345e-06
35.524	1.3e-07	3.4592e-11	5.9261e-07
35.528	5.4403e-09	3.3308e-10	3.3126e-08
35.529	3.1871e-07	1.4917e-09	1.7199e-06
36.185	7.1591e-08	1.1224e-06	5.9359e-07
36.186	4.2725e-08	8.2367e-07	4.6874e-07
36.189	6.3374e-08	1.0825e-06	5.9107e-07
39.523	3.5173e-07	5.332e-07	1.2066e-06
39.581	1.7859e-08	6.3128e-07	1.6624e-06
39.643	1.7134e-06	1.0793e-07	6.4061e-07
40.627	3.3102e-07	2.7963e-07	9.6193e-07

40.969	2.1132e-06	1.3226e-07	6.0544e-08
41.133	1.3056e-08	1.0087e-10	7.9973e-08
41.236	2.4742e-07	3.9792e-07	5.9682e-07
41.407	2.376e-06	1.9964e-07	1.9991e-07
42.351	5.6137e-09	1.1454e-07	9.8225e-08
42.359	1.3793e-08	1.4894e-07	1.012e-07
46.74	9.7492e-08	2.4186e-07	1.3061e-05
46.839	1.1553e-07	8.3324e-07	4.2089e-05
47.078	7.7158e-08	8.5636e-08	3.3462e-06
47.209	6.5172e-07	9.1317e-07	3.7971e-05
49.023	1.6477e-06	1.4779e-06	7.0376e-07
49.066	9.0204e-07	1.97e-06	2.777e-06