Results on Experimental Data Analysis of Independent Cart Systems in Non-Stationary Conditions

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Abstract

This paper presents an analysis of the vibration data obtained from an independent cart system. The study focuses on comparing the vibration data collected with and without the presence of outer race faults, while the 12 roller cart/mover maneuvers at different speeds. Vibration data was captured using accelerometers positioned along the system and acquired through the Beckhoff PLC and National Instrumentation data acquisition systems. The data acquisition process involved running the mover under no-load conditions with and without an outer race fault, at speeds of 500 mm/s and 3000 mm/s. The analysis revealed valuable insights into the behavior and characteristics of the signals under different conditions. Results indicated that envelope analysis in the frequency domain is effective in identifying fundamental frequencies related to the system's dynamics. The calculated frequencies associated with the rotational speed of the mover and the outer race frequency provided a further understanding of the system's behavior.Despite some frequency smearing due to the the non-stationary conditions, fault frequencies were identifiable. The maximum peak hold plots demonstrated that at low speeds, the fault-related frequencies were more susceptible to noise interference, while at higher speeds, the fault frequencies became more prominent and distinguishable. This study contributes to the overall understanding and diagnosis of potential faults within independent cart systems, with further analysis planned to precisely identify the fault frequencies.

1 Introduction

The advancement in linear motors brought about by independent cart technology has overcome the limitations of traditional conveyors that rely on gears, chains, and belts. This innovative technology utilizes linear motors to independently move carts along a predetermined track. The carts are designed with permanent magnets, while the linear motors are equipped with coils that generate a magnetic field, enabling synchronized movement with the changing magnetic pattern.By utilizing magnets, independent cart technology achieves precise control over motion with a minimum number of mechanical components involved, in comparison to conventional conveyor systems. A notable feature of this technology is its frictionless propulsion mechanism, eliminating physical contact between the cart and the linear motor coils. This significantly minimizes wear and tear on individual parts and streamlines the transportation or movement process. This efficient solution reduces energy consumption, operational costs, and enables quick start and stop capabilities without compromising movement control, providing a distinct advantage over traditional conveyors. This feature increases system throughput while mitigating risks such as material loss or damage associated with stopping and starting operations.The versatility of independent cart technology allows for precise and seamless manipulation and movement across a wide range of speeds, making it highly suitable for various industrial applications. Its ability to adapt to diverse operational requirements further enhances productivity and offers potential optimization of industrial processes.

However, it is important to consider the substantial initial cost and significant upfront investment required for installing the independent cart system. While these systems are economically feasible for industries as long as they remain operational uninterrupted, it is crucial to recognize that prolonged downtime can undermine their economic viability. Therefore, the condition monitoring of these systems is essential to ensure optimal performance and long-term economic benefits. Timely detection of potential issues and the implementation of necessary measures can prevent or mitigate damage, reduce the risk of system downtime, and safeguard the investment made in this technology.

Condition monitoring can be broadly categorized into two main types: Permanent monitoring and Intermittent monitoring. Permanent monitoring is used to protect critical and expensive machines by continuously observing their condition and immediately shutting them down upon detecting any abnormalities. However, this technique requires costly transducers to be integrated into the machines during the design stage. On the other hand, Intermittent monitoring involves offline data processing for detailed analysis of the machine's condition. This approach not only offers a cost-effective solution for condition monitoring but can also be used in conjunction with permanent monitoring. Intermittent monitoring can also provide early warnings of developing conditions, allowing for proper planning of maintenance work. Hence, it is a simple and economical choice for monitoring independent cart systems as it does not require customization or design modifications to incorporate specialized transducers[2].

To effectively perform condition monitoring in an industrial process, it is crucial to have a comprehensive understanding of the working principles of different machines, suitable transducers for data collection, the types of signals emitted from various machine parts, and signal processing techniques for analysis.Various analysis techniques, such as Performance Analysis, Acoustic Emissions, Vibration Analysis, Lubricant Analysis, and Thermography, can provide insights into the internal condition of machines using specialized transducers. However, certain techniques are more suitable for specific applications or require specialized transducers. For example, Performance Analysis utilizes simple process parameter transducers like Temperature, Pressure, and Flowrates to determine machine efficiencies and overall condition. Thermography measures small temperature variations and compares them to standard conditions, while Lubricant Analysis examines metallic debris and performs chemical analysis of lubricants to evaluate the machine's internal condition. Vibration Analysis, which offers advanced warning of impending failures, is a widely applicable technique. Machines generate vibrations known as mechanical signatures, which are directly linked to cyclic machine events such as shaft speed and gear-teeth mesh. Changes in the machine's mechanical signature can be detected using various types of transducers. While both Vibration Analysis and Acoustic Emissions can provide warnings of impending failures, Acoustic Emissions are more complex to use for machine condition monitoring[2].Considering the independent cart system used in this study do not involve lubricants, parameters like pressure and flow rate are not applicable. Additionally, the frictionless motion of the carts results in minimal temperature variation during operation. Therefore, the preferred choice for condition monitoring of independent cart systems is to analyze their mechanical signature using vibration analysis.

Our research focuses on the intricate task of diagnosing and analyzing bearing faults and track faults, which pose a multitude of challenges. These challenges encompass various aspects. Firstly, the guide rollers not only need to rotate but also move laterally along the track, synchronizing with the motion of the mover. Secondly, the bearings themselves are of a small size, adding to the complexity of detection and analysis. Thirdly, multiple guide rollers are incorporated within each mover to ensure continuous movement even when one or more bearings are faulty. Lastly, as the number of movers increases, the problem becomes increasingly intricate, making it arduous to pinpoint the exact location or source of the fault.

Researchers have adeptly employed an array of signal processing techniques for condition monitoring of industrial machines. Notable among these analysis tools (although not an exhaustive list) are Envelop analysis, Cepstrum analysis, Discrete Random Separation (DRS), Time Synchronous Averaging (TSA), Spectral Kurtosis, Short time Fourier transform (STFT), and Cyclic Modulation Spectrum(CMS). Through the application of these techniques, the hidden patterns and fault indicators within the machinery can be unravelled. Envelop analysis[6] is one of the fundamental techniques that offers valuable insights by extracting the characteristic features enveloping the machinery's signals. Scrutiny of these signal envelopes can discern intricate patterns and variations that might indicate potential faults. The authors of [10, 11] employed Discrete Random Separation (DRS) for the diagnosis of bearing faults. This technique effectively separates the stochastic components from the deterministic ones within the machinery's signals. This separation not only provides clarity but also facilitates a more refined analysis by allowing a focus on the random nature of vibrations and distinguish them from other patterns or signals within the machinery. Other techniques utilized for the purpose of segregating the discrete and random components within signals include Cepstrum pre-whitening and Time Synchronous

Averaging (TSA). In a study conducted by [8], Cepstrum pre-whitening was employed to diagnose bearing faults under variable speed conditions. Moreover, a comprehensive comparison of various methods pertaining to cepstrum analysis is presented in [7]. Notably, [9] presents several techniques along with their respective advantages and disadvantages for the separation of discrete and random components. Spectral Kurtosis is an insightful statistical measure that highlights the presence of impulsiveness or non-Gaussianity within signals. By scrutinizing the spectral kurtosis, it becomes possible to identify the frequency range that requires further analysis to uncover fault patterns. To ensure accurate results, it is recommended to appropriately filter the signal prior to applying this tool, thereby mitigating the risk of false detection of transients, as this technique exhibits a bias towards the impulsive nature of the signal. Instances of utilizing this tool for fault diagnosis can be found in [3, 4]. Another intriguing tool for signal analysis is the Short Time Fourier Transform (STFT), which offers a comprehensive understanding of the machinery's signals in both the time and frequency domains. This technique enables the analysis of machinery vibrations by decomposing signals into their constituent frequency components over time. Through the examination of how these frequency components vary over time, valuable information about hidden patterns or irregularities can be identified, potentially indicating an impending failure. An interesting example illustrating the application of STFT for diagnosing bearing faults under varying speed is presented in [5].

This paper presents the preliminary results obtained from analyzing the vibration data of the independent cart system. The main objective of this study is to compare the vibration data acquired when the mover is operated at different speeds, both with and without the presence of outer race faults. This comparison enables a comprehensive understanding of the impact of outer race faults on the vibration patterns and helps identify key differences in the data collected in different scenarios. It is structured into several sections. Section 2 provides a concise overview of the experimental setup employed. Section 3 outlines the vibration data, while section 4 provides a detailed account of the raw data and presents the preliminary results. The paper concludes with section 5, summarizing the key findings and conclusions.

2 Experimental Setup

The independent cart system utilized in this study is known as the Extended Transport System (XTS) [1]. It is a modular linear transport system designed for efficient and reliable movement of materials, products, or components in various applications. Comprised of linear motors, movers, and guide rails, these components collaborate to form a flexible and dynamic platform for precise and speedy load transportation (as depicted in Figure 1). The linear motors generate magnetic fields that propel the movers along the guide rails, eliminating the need for belts, chains, or gears. This enhances system efficiency, reduces maintenance requirements, and minimizes noise levels. The movers themselves can be customized to accommodate specific load requirements and support weights ranging from a few grams to several kilograms. Notably, the XTS offers the advantage of being configured into different geometric path shapes. By combining motor modules in various ways, complex path patterns can be created, precisely following the desired trajectory of the load. This versatility enables the XTS to be utilized across a wide range of applications, from simple point-to-point transfers to intricate multi-axis movements. Moreover, the system's flexibility simplifies integration with other automation technologies such as robots, conveyors, and assembly systems, facilitating the creation of highly efficient and integrated production lines.

In our investigation, we utilized a closed-loop path configuration spanning 1500mm or 1.5 meters. This setup incorporated four motor modules: two straight modules and two 180-degree clothoid modules, as depicted in figure 2. This study focused on two types of carts/movers: a 12 roller mover and a 6 roller mover, as shown in figure 3. However, a detailed discussion regarding the specific applications of these movers falls outside the scope of this article. It is worth noting that this system possesses the flexibility to be configured into multiple stations, allowing for the implementation of individual speed profiles for each section. A station refers to a specific section along the track, which can be defined and configured within the XTS application software during the system setup.

In order to capture the vibration data, we positioned two accelerometers on the system, represented by the green and purple dots in the figure 2. One of the accelerometers is suitable for measuring vibration data along a single axis (mono axial), while the other is capable of measuring vibration along three axes (triaxial). Specifically, the mono axial accelerometer is mounted along the z-axis of the triaxial accelerometer. To ensure

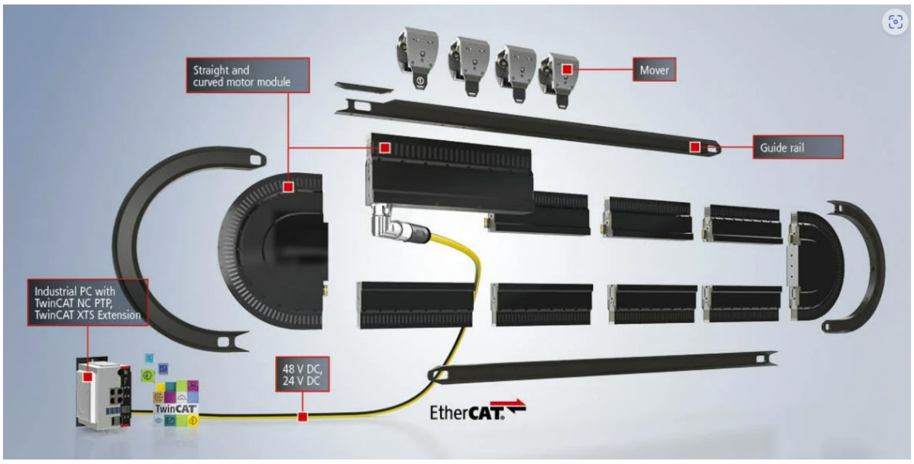

Figure 1: Essential Components of Extended Transport System (XTS) [1]

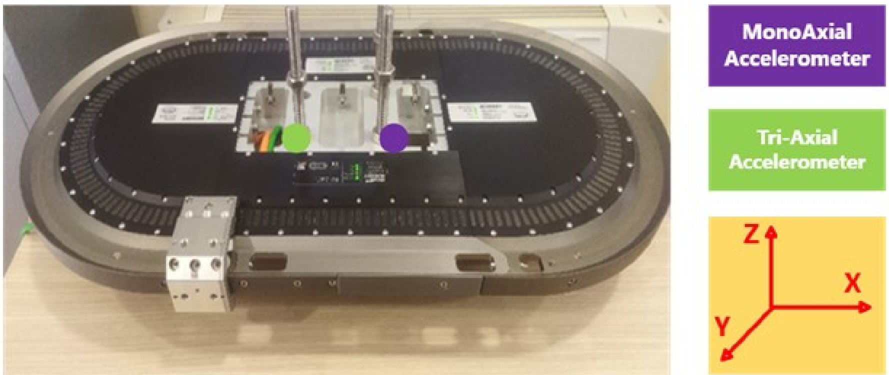

Figure 2: Experimental Setup with Single 12 Roller Mover

comprehensive data collection, we employed two separate data acquisition systems, namely the Beckhoff analog input card and National Instrumentation data acquisition systems. These systems enable us to acquire data from the accelerometers at different sampling rates, providing a more comprehensive and detailed understanding of the vibration characteristics present in the system.

3 Vibration Data

The data acquisition process involved capturing measurements using a single mover in two distinct conditions: a no-fault scenario representing a healthy system state, and a faulty scenario with a straight cut outer race fault. The fault, characterized by a 1mm width and slightly less than 1mm depth, was introduced to simulate an anomalous condition (see figure 3).

To ensure comprehensive data acquisition, we utilized two separate systems: the Beckhoff PLC data acquisition system and the National Instrumentation DAQ. These systems offered the capability to acquire data at different sampling frequencies, providing flexibility in capturing a wide range of information. Specifically, the Beckhoff PLC allowed sampling at a rate of 20 kHz, while the NI DAQ enabled a higher sampling rate of 51.2 kHz. During each measurement cycle utilizing the PLC analog input, the mover was set in motion along the track for a duration of 120 seconds. Similarly, for measurements involving the NI Data Acquisition system, the mover traversed the track for approximately 300 seconds. During the course of these measurement cycles, the mover was run under no-load condition, with and without the presence of an outer race fault. To examine the effects of different speeds on the recorded data, the mover was tested at two distinct velocities: 500 mm/s and 3000 mm/s. By using different set speeds, we aimed to observe potential differences in the vibration signatures and capture any speed-dependent patterns associated with the presence or absence of faults.

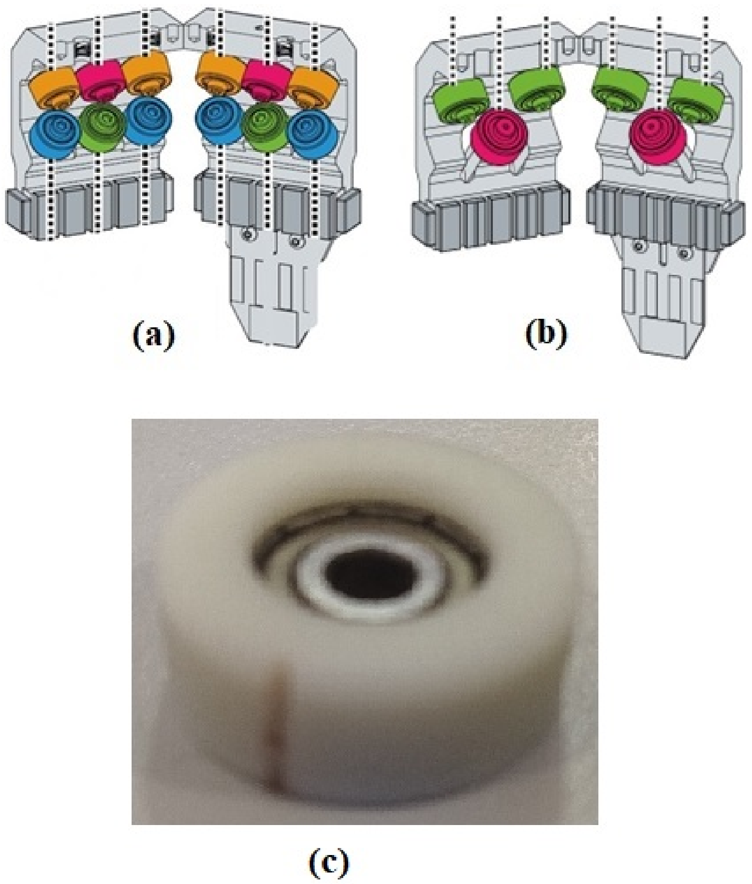

Figure 3: (a): 12 Roller Mover, (b): 6 Roller Mover, (c): Roller Outer Race Fault

4 Preliminary Results

This section focuses on the results obtained from the data collected using the Beckhoff PLC in conjection with analog input card EL3632. The data was acquired at a sampling frequency of 20kHz.

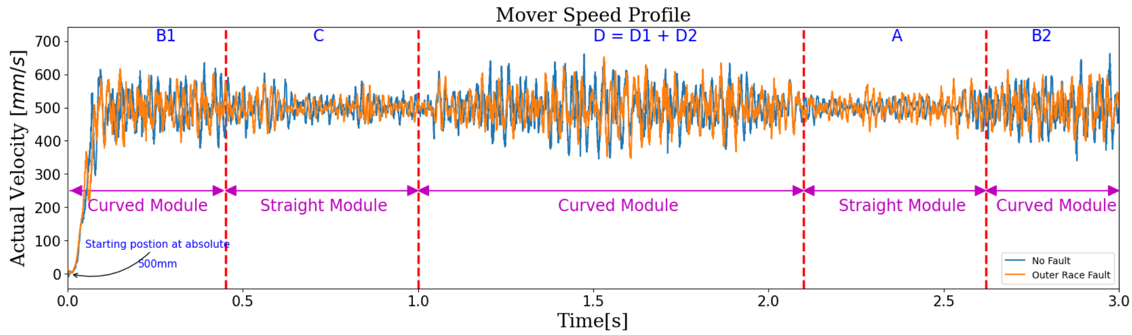

Figure 4: Mover's Speed Profile with Set Speed of 500mm/s

The entire XTS track is divided into six sections, as illustrated in Figure 5. Since the system is configured as a closed-loop path, the positions of absolute 0mm and 1500mm coincide. To avoid any confusion, during each test, the mover initiates and concludes its movement at the absolute position of 500 mm along the track. In Figure 4, a speed profile of the mover corresponding to each section is presented, highlighting the non-stationary nature of the system. It is evident that the curved module exhibits a higher level of energy. This observation could be attributed to a variety of factors, such as the involvement of different sets of rollers in the straight and curved tracks, or the influence of centripetal force. It is possible that a combination of these factors

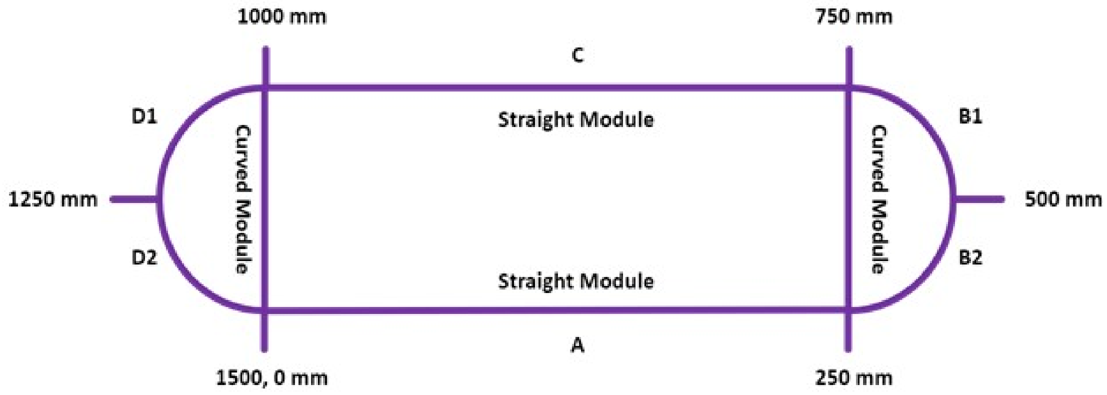

Figure 5: Schematic Diagram of the Experimental Setup with Absolute Position Markers

contributes to the observed energy variation in the curved module.

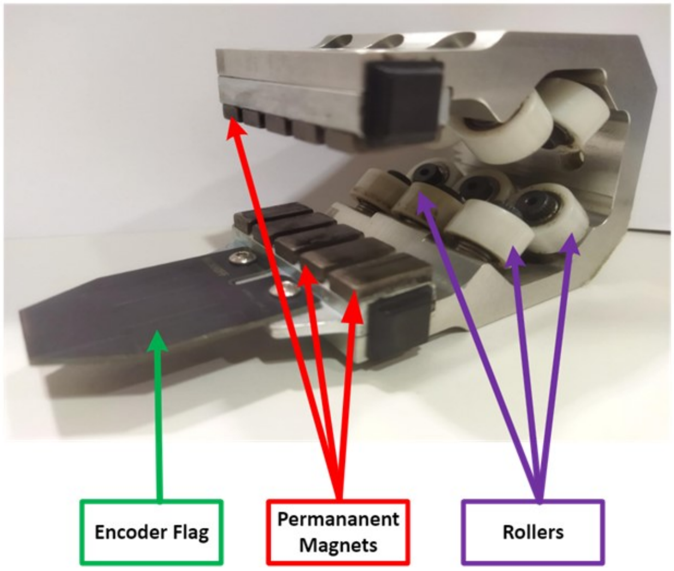

Figure 6: 12 Roller Mover used in Experimental Setup

The data used in this study specifically pertains to the 12 roller mover, which has a length of 50 mm. The mover is equipped with 5 pairs of permanent magnets, positioned on both sides of the mover. The spacing between each magnet is 4.7 mm (see figure 6).

Figure 7 shows the raw data collected for two complete revolutions of the mover, both in the presence and absence of an outer race fault. The data was acquired as the mover moved along the track at a speed of 3000 mm/s. As the distinction between the signals with and without the presence of an outer race fault is not readily apparent in the time domain, an envelope analysis was employed to investigate the characteristics of the signals in the frequency domain. By utilizing envelope analysis, the fundamental frequencies associated with the system's dynamics can be identified in an intuitive manner. For instance, Figure 8 and Figure 9 depict the frequency components of 0.3 Hz and 2 Hz, respectively. These frequencies are directly related to the rotational frequency of the mover, specifically at speeds of 500 mm/s and 3000 mm/s.

The diameter of the each of the mover's roller measures approximately 15.96 to 16 mm, resulting in a rotational speed of 62.5 radians when the mover moves at a speed of 500 mm/s. By converting this value to revolutions per second, yields a frequency of 9.9490 Hz, which corresponds to the rotational frequency of the outer race. Likewise, when the mover's speed increases to 3000 mm/s, the outer race frequency of the roller reaches 59.71 Hz. Additionally, taking into account the mover's length of 50 mm, we can determine the rotational frequency component by dividing the mover's linear speed of 500 mm/s by its length. This

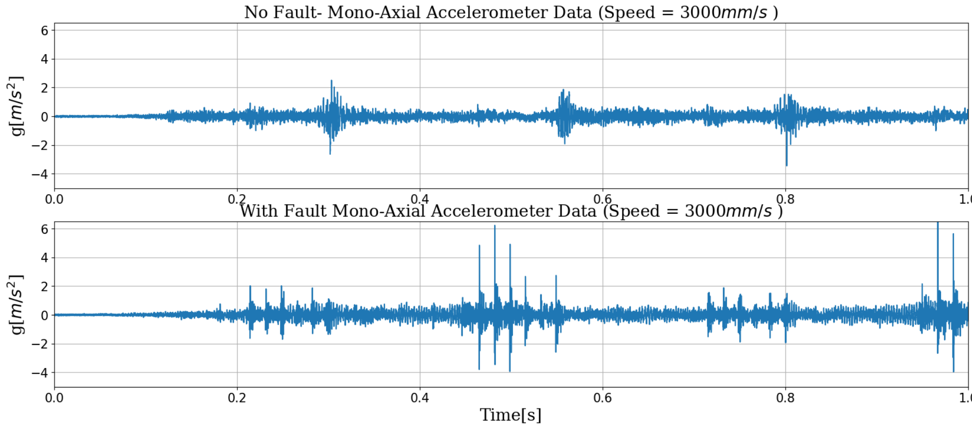

Figure 7: Vibration Data Acquired at the Mover Speed of 3000 mm/s

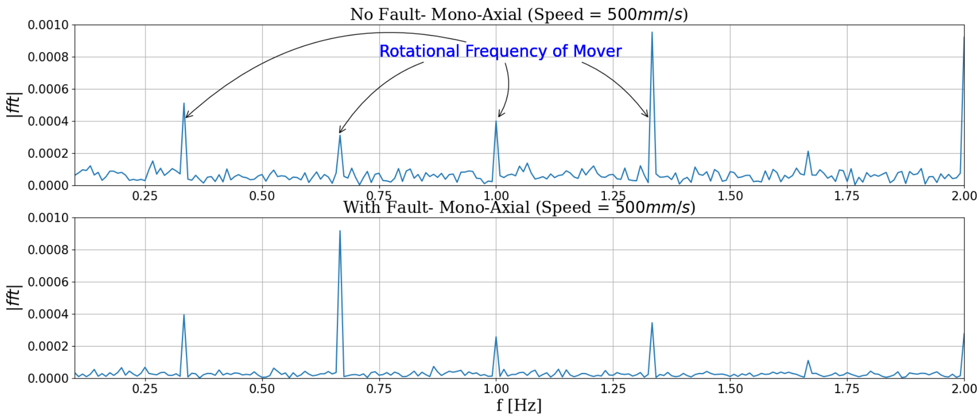

Figure 8: Frequency Component Related to the Mover's Speed = 500 mm/s

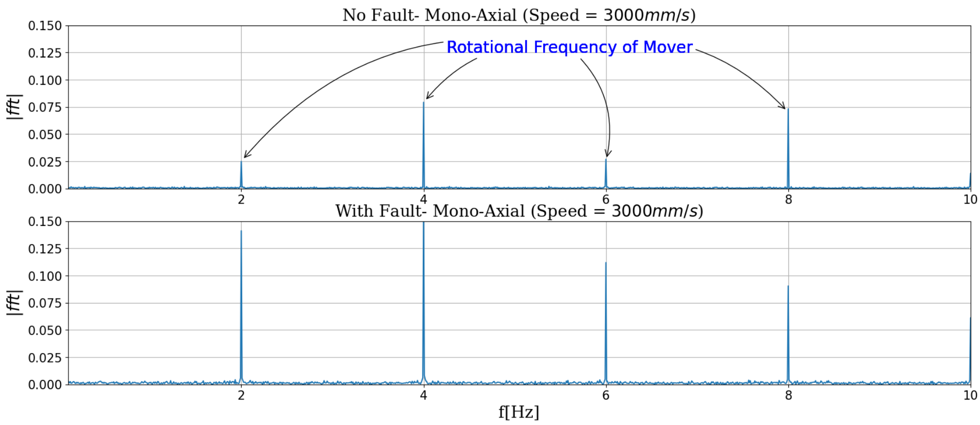

Figure 9: Frequency Component Related to the Mover's Speed = 3000 mm/s

calculation yields a frequency of 10 Hz. These simple but important calculations provide valuable insights into the relationship between the mover's roller diameter, rotational speed of the outer race, and linear speed of the mover, showcasing the corresponding frequencies associated with the mover's motion.The visualization of these frequency components provides valuable insights into the distinctive features and patterns exhibited by the signals, aiding in the understanding and analysis of the system's behavior, particularly in relation to the presence or absence of an outer race fault.

Through the aforementioned calculations and by closely examining the desired frequency windows, the

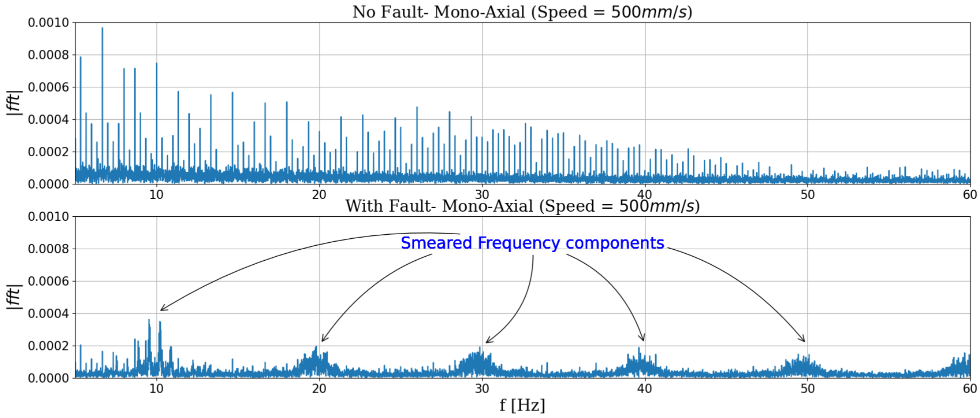

Figure 10: Smeared Frequency Component Related to the Roller Outer Race Fault at Speed = 500 mm/s

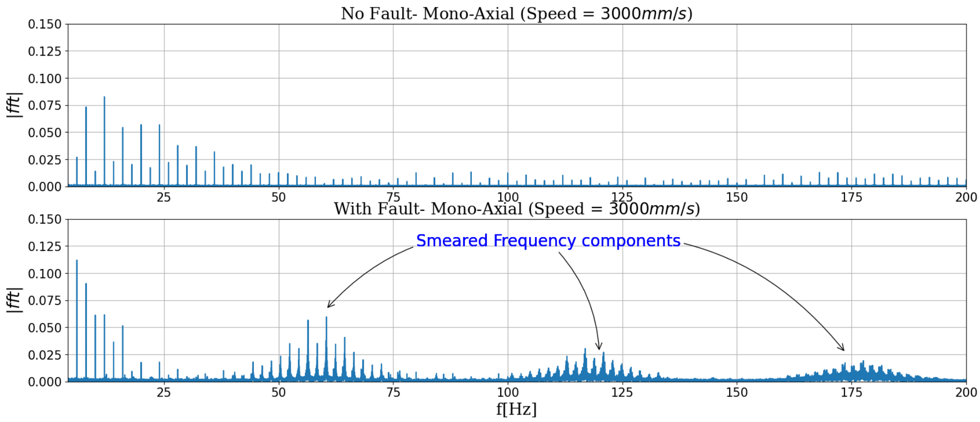

Figure 11: Smeared Frequency Component Related to the Roller Outer Race Fault at Speed = 3000 mm/s

fault frequencies become readily apparent in Figure 10 and Figure 11. However, it is worth noting that there is a slight blurring or smearing of the frequencies observed in these figures. This phenomenon can be attributed to the non-stationary condition, which means that the speed is not constant along the track. It could also be due to the slipping of the roller outer race, or it could be a combination of both factors. The close proximity of these phenomena introduces a certain level of complexity and overlap in the signals, making it challenging to isolate and distinguish individual fault frequencies. Despite the smearing effect, the results still offer valuable insights into the presence and characteristics of the fault frequencies, contributing to the overall understanding and diagnosis of potential faults within the system. However, further analysis is needed to more precisely identify and delineate the specific fault frequencies.

By examining the maximum peak hold plots (refer to Figure 12 and Figure 13), an intriguing phenomenon becomes apparent. Both the signals obtained with and without outer race faults exhibit their highest magnitudes within the same frequency bands, indicating a lower signal-to-noise ratio at low speeds. However, as the speed increases, the maximum peak hold gradually shifts towards higher frequencies, clearly highlighting a discernible difference between the two signals. This observation implies that at lower speeds, the presence of noise hampers the clarity and distinction of the fault-related frequencies. However, as the speed escalates, the fault frequencies become more pronounced and separated from the noise, enabling a clearer identification and differentiation between the signals with and without outer race faults.

5 Conclusion

The comparative analysis of the vibration data obtained under different operating conditions reveals that fault indications become more prominent at higher speeds of the mover. However, the fault signatures are

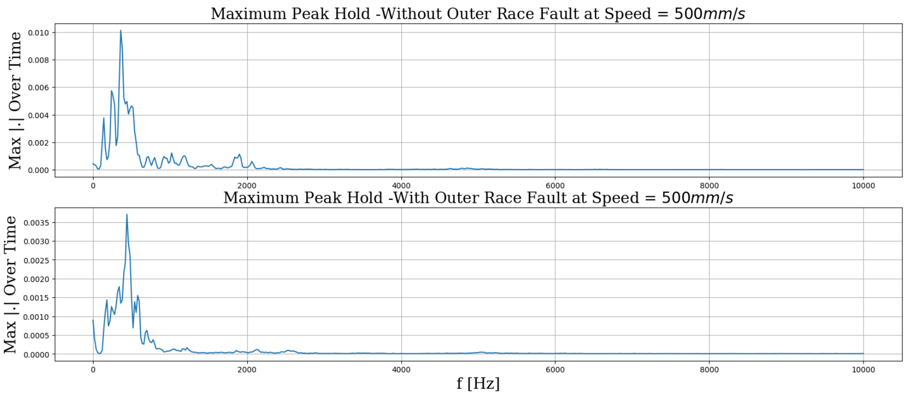

Figure 12: Maximum Peak Hold at Speed = 500mm/s

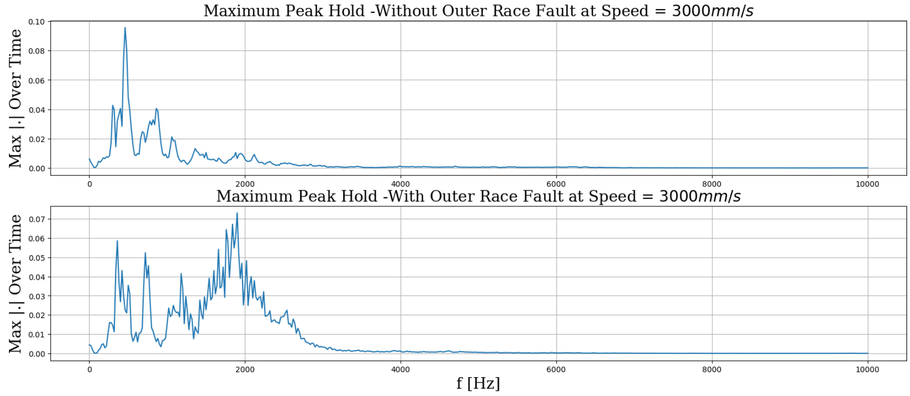

Figure 13: Maximum Peak Hold at Speed = = 3000mm/s

heavily masked and buried within the signal. Envelope analysis provided some weak indications of the fault frequencies; however, a more in-depth analysis is required to accurately identify the desired outer race fault frequency. To achieve this, a comprehensive signal processing strategy should be employed to clearly identify faults regardless of the operational speed of the mover. Additionally, a comparison of vibration data under loaded conditions with the data obtained under no-load conditions should be conducted. This comparison will provide further insights into the effects of varying loads on fault detection and diagnosis.

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