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Experimental Investigation of the Impact of Misalignment Defects on the Vibration Behavior of Drive Systems using Various Coupling Types (Elastic and Rigid) in Rotating Machinery and Power Generation Equipment

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ABSTRACT

This study explores how misalignment affects vibration patterns in drive systems using two common types of couplings: elastic (Rotex GS) and rigid flange couplings. By measuring vibrations in both vertical and horizontal directions under controlled conditions, the research reveals that vertical vibrations are consistently more intense than horizontal ones. In systems with elastic couplings, the stiffness of the material strongly influences how vibrations are transmitted and, in some cases, increases the risk of failure. Rigid couplings, on the other hand, produce unique vibration signatures when misaligned, making it easier to detect mechanical issues. The type of misalignment matters too: axial misalignment causes strong, low-frequency vertical vibrations, while radial misalignment results in more complex patterns. These findings highlight the need to monitor vibrations in both directions and suggest that the ratio of vertical to horizontal vibration could serve as an early warning signal, helping teams catch problems sooner and plan maintenance more effectively.

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Introduction

For decades, vibration analysis has been a key technique in condition-based preventive maintenance in the industrial sector [1]. This non-destructive method assists in monitoring equipment, diagnose faults, and track the deterioration of mechanical components over time [2]. In industryy, the signals of vibration are caused by a mix of different sources caused by the various parts of the machines [3]. Note that these signals are complex, it is important to define how damaged a particular component is [4]. Also, we need to separate the different vibration sources to identify which ones are causing a fault, in a specific mechanical part [5]. This separation is done by taking multiple measurements with accelerometers placed on the structure [6]. Furthermore, this method of separation the sources ofvibration helps, not only to determine where faults are on mechanical parts, but also to measure and track how their condition degrades gradually [7]. This method aims to enhance the accuracy and reliability of the diagnosis [8].

Recently, several investigations have highlighted the importance of vibration analysis for predictive maintenance and diagnosis of complex mechanical systems. Applications cover many industries, such as monitoring vibrations in ship windings, rotating machinery, and power generation equipment, following established international standards and addressing specific misalignment challenges in various mechanical systems [9,10].

In this context, our research focuses on studying the influence of misalignment defects of different types of couplings in drive systems on the characteristics of vibration velocities.In this study, we analyzed the impact of rotational speed by systematically varying several experimental parameters: the measurement direction (horizontal and vertical) and the type of coupling-rigid couplings under nominal conditions and exhibiting specific defects (planar misalignment, radial misalignment), as well as elastic couplings with different elasticity characteristics, represented by distinct colored rings (blue, yellow, red, and green).

Despite extensive work on vibration analysis and condition monitoring, existing studies often overlook the combined effects of coupling type, material stiffness, and misalignment direction on vibration behavior in rotating machinery. Most prior research either focuses on a single direction of vibration (typically horizontal) or treats coupling types generically, without accounting for the detailed mechanical properties, such as the elasticity of different RotexGS coupling materials. Furthermore, the diagnostic value of vibration anisotropy (differences between vertical and horizontal vibrations) remains underutilized in early fault detection. This study addresses these gaps by experimentally comparing elastic and rigid couplings under controlled misalignment conditions, measuring bi-directional vibrations, and proposing the vertical-to-horizontal vibration ratio as a practical diagnostic tool for predictive maintenance.

Experimental Setup and Test Equipment

The test bench used in this study features a three-phase electric motor fitted with an encoder, all mounted on a base plate that includes a precision alignment system. The motor is controlled by a frequency converter, which allows smooth and accurate adjustment of its rotational speed (see Figure 1).

This control unit is also equipped with specialized instruments, such as a digital tachometer for real-time speed measurement and an integrated wattmeter to monitor the electrical power consumption of the motor during the experiments.

As shown in figure 1, the experimental setup consists of two rigid bearings:

- **P1:** is a rigid bearing positioned on the motor side, secured by two locking rings tightened on the shaft to hold it in place axially and prevent any movement;
- **P2:** is a free rigid bearing located at the far end of the shaft.

There are two piezoelectric sensors placed horizontally and vertically to convert vibrations into electrical signals, along with a reference sensor that measures the rotational speed. In addition, the setup includes two types of couplings: an elastic ROTEXR GS and a rigid plate coupling, plus an amplification and digitizing system to process the data on a computer.

The study provides useful insights into vibration behavior caused by misalignment in machinery but focuses only on a limited range of misalignments and coupling types. It lacks long-term data and does not consider varying loads or more complex vibration patterns. Expanding the scope and including dynamic conditions would enhance its real-world relevance.

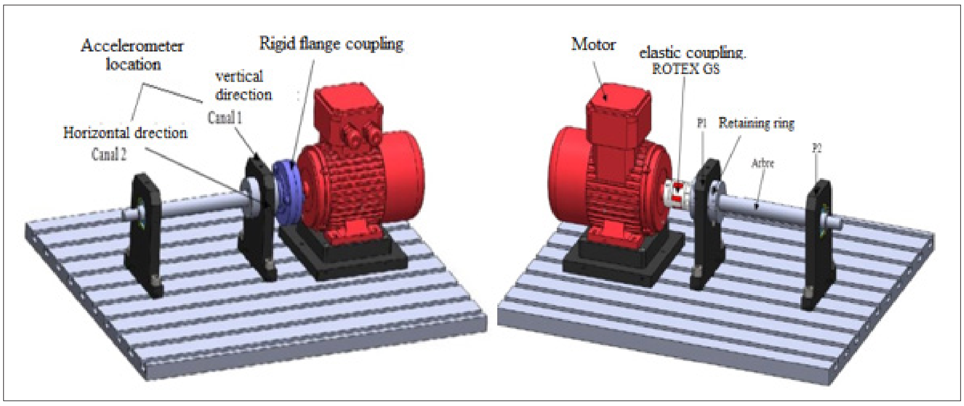

Figure 1: Experimental Setup

To ensure the reliability and consistency of the experimental results, multiple test runs were conducted under identical conditions for each coupling type and misalignment scenario. The tests were performed to assess the repeatability of the vibration measurements and to ensure that the observed trends were not due to random variations or measurement errors.

Elastic Couplings of the Rotex Type

ROTEX® GS couplings have a clever three-part design made up of an elastomer ring sandwiched between two metal hubs. They are assembled by pressing them together axially under tension, which creates a tight, backlash-free connection (see figure 2).

Figure 2: Experimental Setup

These couplings are widely used across various fields, especially in precision measurement and control systems. One of their main benefits is their easy installation, enabling compact setups that can be quickly and effortlessly adapted to a range of technical applications.

The ROTEXR GS elastic couplings used in this experimental study come in four versions, each with a different Shore hardness. They are distinguished by their distinct colors, and each has its own specific supplier reference.

Rigid couplings, on the other hand, are built for precision. They create a strong, fixed link between shafts but don't handle misalignment well. Even small alignment issues can lead to higher vibrations, extra stress on bearings, and potential mechanical failure.It's important to know how different types of couplings react when misaligned—this helps spot potential issues early and make better maintenance choices. This study takes a closer look by comparing how elastic and rigid couplings perform under various conditions. By testing couplings with different hardness levels, the research explores how elasticity affects the way vibrations move through the system. These tests give valuable insight into how the mechanical properties of each coupling influence overall vibration behavior and machine performance.

The table 1 gives a clear summary of the main characteristics of the ROTEXR GS coupling. It covers important details such as the different hardness levels available, each identified by a specific color, the materials used in their construction, the range of temperatures they can safely operate within, the sizes offered, and the typical applications for which each type is best suited. This overview facilitates understanding how these couplings can meet various technical requirements across different industries.

Table 1: Characteristics of a ROTEXR GS Coupling

Ring designation hardness - [shore]	Color Identification	Material	Authorized temperature range [°C]		Coupling sizes	Application characteristics
			Temperature	Max momentary		
80 Sh-A-GS	 Blue	Polyurethane	-50 to +80	-60 to +120	5 to 24	-Electronic metrology system control. - No play in the pre-stress zone.
92 Sh-A-GS	 Yellow	Yellow	-40 to +90	-50 to +120	5 to 55	- Good damping, medium elasticity. - Electronic metrology and control system with synchronous coupling. - No play in the pre-stress zone.
98 Sh-A-GS		Polyurethane	-30 to +90	-40 to +120	5 to 90	- High torque transmission with medium damping. - Electronic metrology and control system with synchronous coupling. - Position drive. - Spindle drive. - High load. - No play in the pre-stress zone.
64 Sh-D-H-GS	 Green	Hytrel	-50 to +120	-60 to +150	7 to 38	- Very high torque transmission with reduced damping. -High ambient temperature resistance, hydrolysis resistant. - For misalignment at critical speeds. - Control, machine tool spindle, linear feed movements. - Planetary reducer with /without play. - High torsional stiffness with limited inversion play.

Rigid Flange Couplings or Disc Couplings

We conducted experimental tests on the setup described earlier, keeping the operating conditions steady at 1000 rpm, and swapping out the different types of couplings one after the other.

The study examined three types of rigid flange couplings:
- **Type (a):** a baseline model with no defects (ARSD);
- **Type (b):** one with a small radial misalignment of 0.2 mm (ARDR);
- **Type (c):** one with an axial misalignment of 0.4 mm that causes a slight angular tilt of 0.25° (ARDP).

Figure 3 shows these three types of rigid flange couplings, making it easy to see the differences between the baseline model and the two misaligned ones. This figure aids in bettergrasp how each type differs in alignment and how that might affect the system's overall performance.

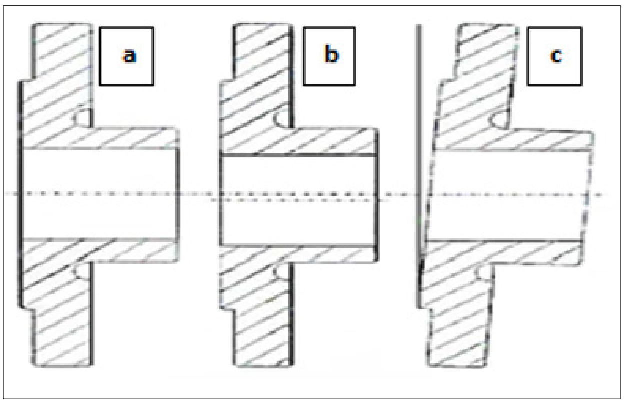

Figure 3: Half Flange Coupling

Results and Discussion

Before presenting the results, it is important to explain the purpose of this study. The analysis examines how different types of couplings, especially Rotex GS elastic couplings, affect the vibration behavior of machines. In addition, this study enables to identify factors that cause wear and to understand failure mechanisms linked to misalignment and coupling materials. The results in the next sections provide helpful information to improve the reliability and lifetime of the mechanical systems studied.

Elastic Couplings of the Rotex GS Type

Figure 4 and Figure 5 illustrate the results of the elastic coupling test at N=1000 rpm for vertical and horizontal vibrations for the four types of couplings. The analysis of these figures shows important effects on the wear and possible damage of machines fitted with these different elastic couplings. This is aligned with recent research in the field, such as Djeddi et al., which investigate coupling misalignments in rotating machinery.

Observations

We observe from these figures that, vibrational anisotropy (differences between vertical and horizontal vibrations) directly affects the deterioration mechanisms of machines. Vertical vibrations (3 to 7 Hz) affect the foundations and fastenings, while horizontal vibrations (around 17 Hz) damage the bearings and alignments.

The four types of couplings show distinct risk profiles:
- **Red Coupling:** high vertical amplitude, high risk for bearings.
- **Green Coupling:** specific energy concentrations, risk of destructive resonance.
- **Yellow Coupling:** complex energy distribution, risk of beating and multidirectional fatigue.
- **Blue Coupling:** balanced behavior, more predictable degradation.

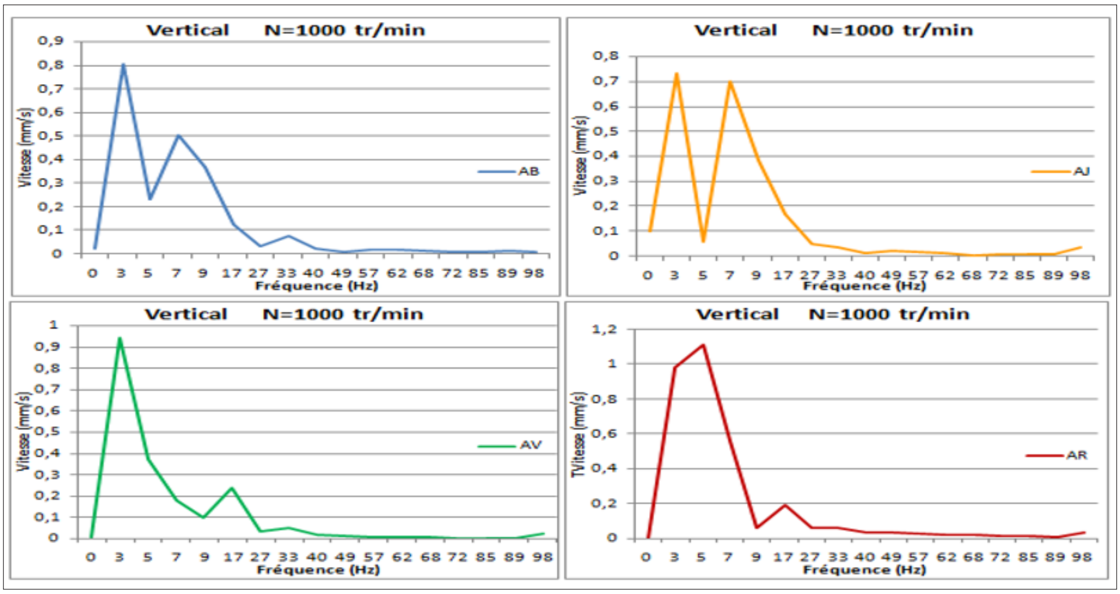

Figure 4: Results of the Elastic Coupling test at N = 1000 rpm (Vertical Vibration)

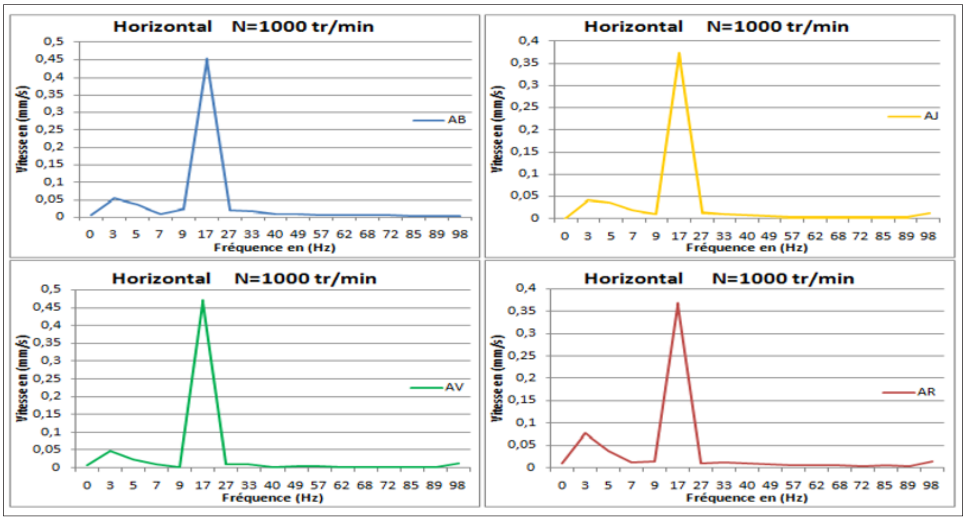

Figure 5: Results of the Elastic Coupling test at N = 1000 rpm (Horizontal Vibration)

Interpretations

For predictive maintenance, the ratio of vertical to horizontal vibration amplitudes is an early warning sign. Monitoring both directions is important.

This facilitates choosing to decide the right action based on the coupling type:

- Check bearings for the red ring;
- Check alignment for the green ring;
- Verify secure tightening of the yellow ring to prevent vibration-related issues;
- Do regular maintenance for the blue ring.

Rigid Flange Couplings

In rotating machines, misalignment of shafts causes up to 50% of the costs from failures. Making sure shafts are aligned correctly can reduce unexpected machine stops and improve production a lot. Today, companies need to use their equipment well and lower costs. That is why accurate shaft alignment is very important.

We conducted a series of experimental tests on rigid couplings, Figure 6 and Figure 7 show the test results at N = 1000 rpm.

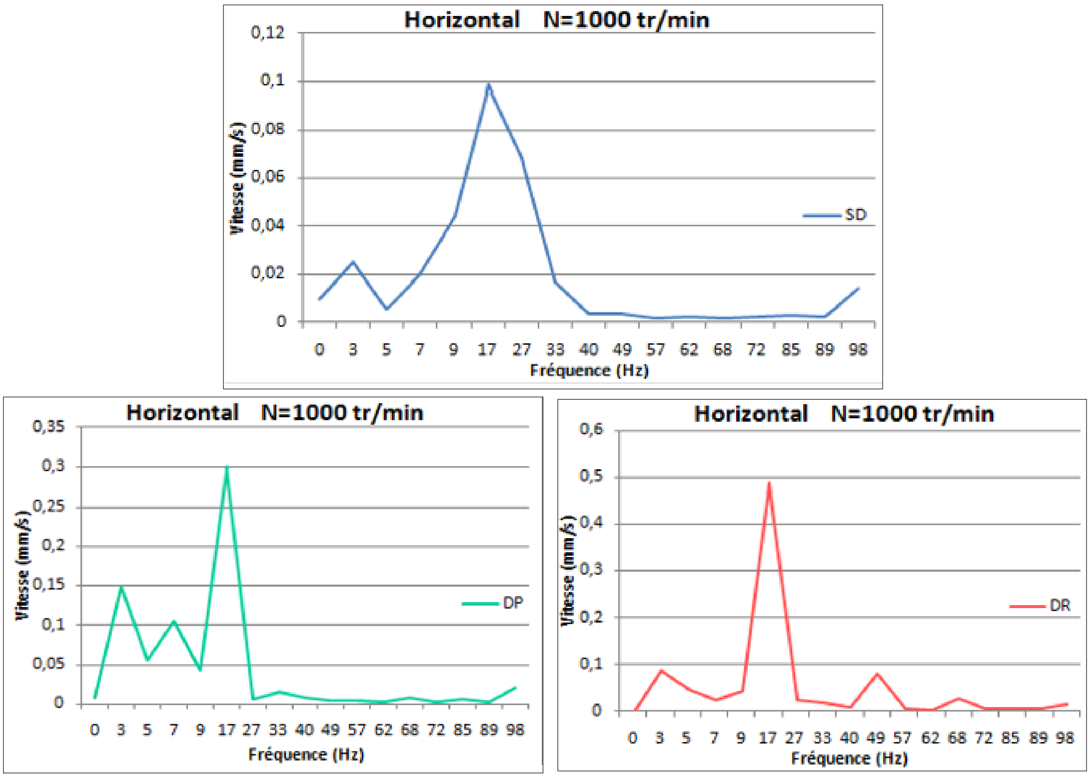

Figure 6: Results of the Rigid Coupling test at N = 1000 rpm (Horizontal Vibration)

Observations

When we compare the two figures showing vertical and horizontal vibrations, the difference is clear. Vertical vibrations are consistently between 2 to 8 times stronger than horizontal ones. This indicates that the machine experiences very different forces depending on the direction, and it is especially vulnerable to damage from those stronger vertical vibrations.

Each type of defect causes wear and tear in its own way. For example, the DP defect creates alternating torque that leads to increased vertical vibrations, while the DR defect brings on multi-frequency alternating stresses that can be especially damaging. By understanding these differences, we can better diagnose problems and develop optimal solutions.

Interpretations

Considering that the machine reacts differently along each axis, it is important to monitor both directions carefully. Focusing only on horizontal vibrations could mean missing critical warning signs that show up in the vertical direction. That is why maintenance teams often set specific alert levels for vertical and horizontal vibrations separately. Also, understanding the exact nature of each defect allows for more targeted repairs. For example, if vertical vibrations are high due to DP, strengthening vertical supports or checking foundations might help. On the other hand, if DR is causing multi-frequency stresses, balancing the machine or fixing alignment issues could make a big difference.

In the end, keeping an eye on how vibrations behave in all directions and tailoring maintenance based on the type of defect is key to preventing unexpected breakdowns and extending the life of the machine.

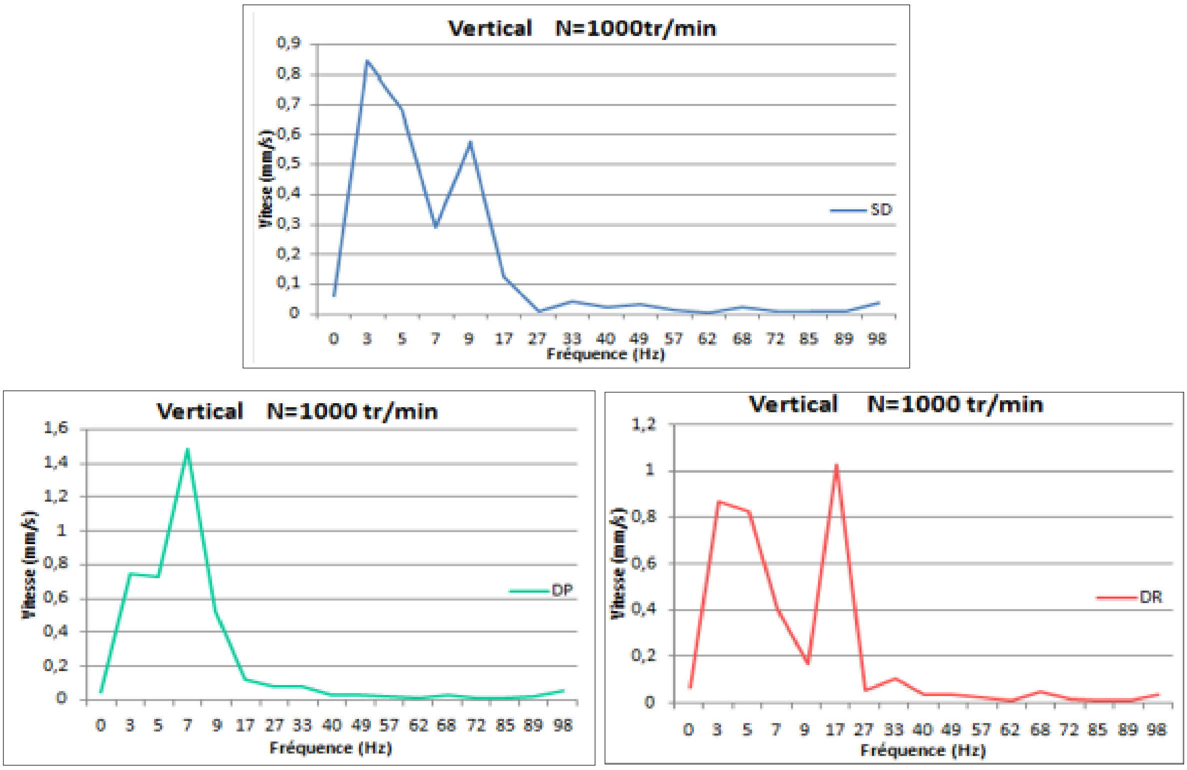

Figure 7: Results of the Rigid Coupling test at N = 1000 rpm (Vertical Vibration)

To ensure effective maintenance, it is important to set specific alert thresholds for each direction, use differential diagnosis based on characteristic frequencies, and tailor interventions to the type of defect. For example, strengthening vertical fixings and checking foundation rigidity can address axial or angular defects, while correcting radial misalignment, performing dynamic balancing, and analyzing support flexibility help with radial defects. Moreover, having bidirectional monitoring plays a key role in accurately predicting potential failure modes.

In real-world machinery, not all vibrations are the same, and some can do a lot more damage than others. From our study, two types of vibrations stood out as the most harmful:

The first one is vertical vibration. These are the up-and-down movements in the machine, and they are not just a little stronger, they can be two to eight times more intense than vibrations from side to side. That extra force puts a lot of stress on the machine's foundations, supports, and bolts. Over time, this leads to parts getting loose, misaligned, or even breaking. If left unchecked, strong vertical vibrations can shut down an entire system unexpectedly.

The second major concern is what happens when there is a radial misalignment, when the shafts are not lined up side to side. This does not just cause simple shaking; it creates complex, multi-frequency vibrations that hit the bearings and shafts in ways that are hard to catch early. These subtle but damaging stresses slowly wear down the components, causing fatigue cracks, imbalance, and eventual failure. It is the kind of problem that sneaks up on you if you are only looking at basic vibration levels.

Together, these two strong vertical vibrations and misalignment-driven stressesare the most destructive. However, the good news is that by monitoring both vibration directions and using tools that notice these patterns early, maintenance teams can fix issues before they turn into major problems. It is about catching the warning signs and taking the right action, whether it is tightening foundations, realigning shafts, or balancing the system properly.

This method helps reduce downtime, costs, and failure risks by enabling early detection of faults through vibration direction analysis, allowing for targeted and timely maintenance interventions.

Conclusion

This comparative study of the vibration properties of different types of couplings made it possible to identify distinct vibration patterns linked to each setup and type of fault. The results show that vibration anisotropy is a reliable indicator of the mechanical systems' wear condition, with vertical vibration amplitudes always being higher (2 to 8 times) than the horizontal ones in all tested setups.

For the elastic couplings of the Rotex GS type, we noticed that the hardness of the elastomer (shown by the color code) strongly affects the system's vibration behavior. The red coupling shows a high risk for the bearings because of its strong vertical vibrations, while the green coupling causes energy concentrations that can lead to damaging resonances. The yellow coupling has a complex energy pattern that promotes beating and multi-directional fatigue, whereas the blue coupling shows a more balanced behavior and a more predictable wear.

For the rigid flange couplings, the alignment faults studied (radial and axial/angular) show specific vibration patterns that help identify them clearly. The axial/angular fault (DP) mainly appears as stronger vertical vibrations at low frequencies (3-5 Hz), while the radial fault (DR) causes vibrations both at low frequencies and at the rotation frequency.

These results show how important it is to monitor both horizontal and vertical directions to understand the machine's condition. The ratio between vertical and horizontal vibration sizes is a very useful early warning sign to predict failures. This method helps improve maintenance plans by adjusting actions based on the type of coupling and the kind of fault found.

While this study focused on elastic and rigid couplings with axial and radial misalignment, future research could dive into other misalignment types, like angular and parallel misalignments, to build a more complete picture of how different defects impact vibration behavior. It would also be beneficial to expand the research by testing a variety of coupling materials beyond just polyurethane and hytrel, and exploring a broader range of operating conditions, such as varying loads, speeds, and temperatures, to make the findings more applicable to real-world situations.

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