

General Introduction to Measurement and Analysis of Torsional Vibration

Introduction to Torsional Vibration

Torsional vibration refers to the oscillation of angular velocity in rotating components, which occurs due to fluctuating torque. It typically arises in systems such as engines, turbines, electric motors, and any machinery with rotating elements.

The importance of understanding torsional vibration lies in its potential to cause mechanical failures if left unchecked. For example, an engine crankshaft can experience non-uniform speed during operation, where the rotational velocity fluctuates despite steady engine RPM.

This fluctuation can induce stress that lead to component fatigue, cracks, or even catastrophic failure in extreme cases. Hence, monitoring and mitigating torsional vibration is critical for system longevity and efficiency.

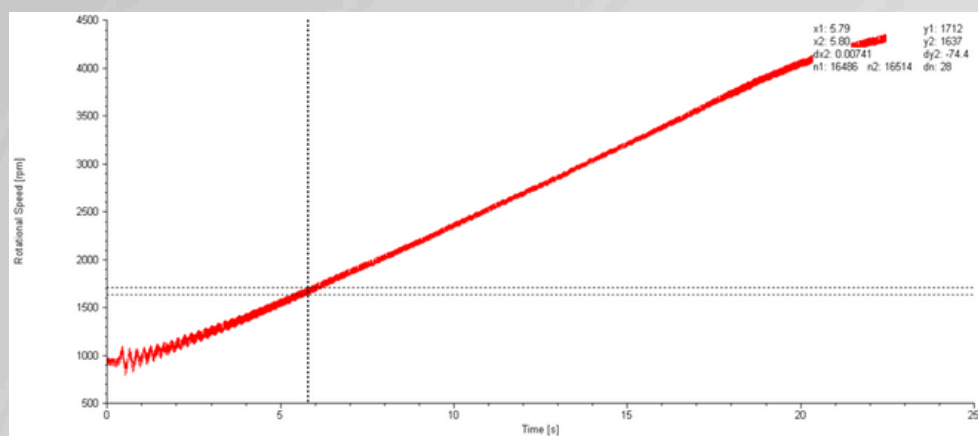


Figure 1 - Rotational speed signal, engine run-up, overview

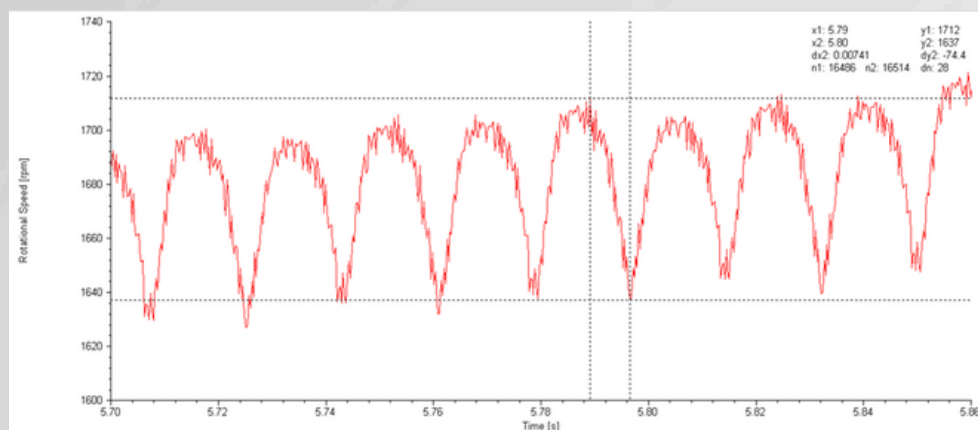


Figure 2 - Rotational speed signal, engine run-up, close view

Why Torsional Vibration Matters

Torsional vibration is a critical factor that can directly influence the performance, durability, and reliability of mechanical systems across a wide range of industries.

In **internal combustion engines**, for instance, fluctuations in crankshaft speed caused by combustion events create cyclical stress, leading to accelerated wear on components such as couplings, bearings, and gears. At the same time, torsional vibration problems are not only caused by compression and combustion but also through load impacts in the entire drivetrain. This is the connection between engine analysis (orders) and NVH (frequencies). These interactions are critical for understanding the dynamic behavior of the system and optimizing its performance. By analyzing these effects, engineers can identify potential weak points and improve the durability and reliability of the drivetrain components. Furthermore, this approach allows for the refinement of noise and vibration characteristics, enhancing overall driving comfort and customer satisfaction.

In **steam turbines**, torsional vibration arises due to the interaction between rotating shafts and the steam flow. Variations in steam pressure can cause fluctuations in turbine speed, which may lead to mechanical stress and failure if not properly controlled. Excessive torsional vibration in turbines can damage critical components like shafts, rotors, and bearings, leading to costly repairs and downtime. For turbines used in power generation, external influences also come into play, such as feedback effects from the grid or sub-harmonics. These factors can significantly impact the stability and efficiency of the turbine's operation. Understanding and mitigating these effects is crucial to prevent potential damage and ensure reliable energy output. Advanced monitoring and control systems are often employed to address these challenges and maintain optimal performance.

In **electric vehicles (EVs)**, torsional vibration affects the electric motor's drivetrain. High-frequency torsional oscillations can result from the rapid acceleration and deceleration characteristics of EV motors. This leads to noise, vibration, and harshness (NVH) issues, which may affect passenger comfort. Additionally, over time, torsional vibrations can increase wear on transmission gears and electric motor bearings, reducing the vehicle's efficiency and lifespan.

In **planetary gearsets for wind energy systems**, torsional vibration poses a unique challenge. These gearsets are responsible for transferring the rotational energy of the wind turbine blades to the generator. Fluctuations in wind speed can cause torsional vibrations, which propagate through the gearbox and lead to misalignment, gear tooth wear, and fatigue failures. If not properly managed, these vibrations can reduce the operational efficiency of the turbine, lead to costly maintenance, and potentially shorten the lifespan of the entire wind turbine system.

Torsional vibration also affects user experience in vehicles and machinery, where excessive vibrations may lead to discomfort or noise, commonly referred to as gear whine or clutch chatter. In industrial applications, unmanaged torsional vibration can cause synchronization issues, lowering the precision of machinery, reducing performance, and increasing operational costs. These challenges underscore the importance of torsional vibration management across a broad spectrum of mechanical systems, highlighting its impact on both performance and longevity.

How to Measure Torsional Vibration

Measuring torsional vibration requires accurate capturing of rotational speed variations, often using sensors that provide multiple samples per shaft revolution. Pulse-per-revolution (PPR) sensors, such as optical encoders, optical sensors or magnetic pickups, are common in such measurements. These sensors produce a signal corresponding to rotational speed at very high frequencies, allowing engineers to detect the smallest fluctuations in speed during each cycle.

A higher PPR provides more detailed data, making it easier to capture torsional vibration phenomena. Instead of using time-based data as typically done in the NVH world, an angle-based measurement approach including the use of high resolution counters in the Gigahertz range proved to be extremely efficient in delivering most accurate results and fast FFT (Fast-Fourier-Transform) data processing due to low size of the measurement data files.

The captured data can then be analyzed using specialized software for rotational data processing to make use of the angle-domain data and to identify frequency and amplitude changes across RPM ranges. This provides valuable insights into system performance.

Example in Automotive Applications

In the automotive industry, torsional vibration is especially relevant. During acceleration, a vehicle's engine produces subtle, rapid variations in RPM due to uneven power output from individual cylinders. While these variations are typically small, they can cause noticeable vibration and noise if they exceed acceptable limits. For instance, drivers may report vibrations in the steering wheel or pedals, or noise from the transmission. In severe cases, torsional vibration can even lead to engine or drivetrain component damage. Therefore, vehicle manufacturers use advanced vibration measurement systems to ensure engines run smoothly and within safe operational limits to enhance both performance and comfort.

Sensors for Measuring Torsional Vibration

Different types of sensors can be used to measure torsional vibration, each offering specific advantages depending on the application. **Magnetic pickups** are one of the most popular due to their robustness, low cost, and ease of use, but they are limited by the number of gear teeth available for measurement.

Optical encoders, which work with zebra tape or zebra disks, can provide higher PPR rates, offering greater precision in detecting minute fluctuations, but they are sensitive to dirt, dust and oil.

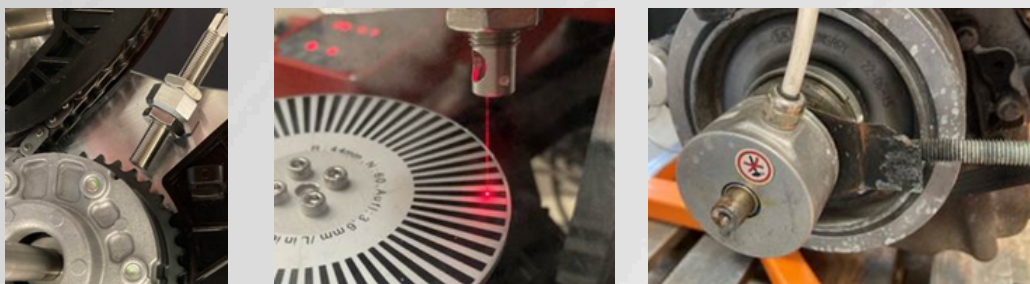


Figure 3 - Magnetic pickup, optical encoder, incremental encoder

High resolution **incremental encoders** deliver sufficient information per revolution which especially allows analysis of high order effects. This is very relevant for transmission error analysis and the identification of gear meshing orders. Selecting the right sensor depends on factors like precision needs and environmental conditions.

With an angle-based data processing the correction of butt joints when using zebra tapes or gear markings like speed drops to 50% of the average when measuring a 60-1 gear wheel, or speed drops to 33% of the average when measuring a 60-2 gear wheel is easily done.

Understanding Torsional Orders

Torsional orders are multiples of the fundamental rotational speed and help identify specific sources of vibration. In engine analysis, the torsional order represents the number of significant torque pulses per revolution. For example, in a 4-cylinder engine, the second order typically corresponds to the firing events, making it a key diagnostic tool for understanding vibration sources.

At the same time, we know that this only applies if the pulses are purely sinusoidal. However, since they are not, harmonics are generated in the spectrum.

The actual number of torque pulses is determined by the engine's firing order and the nature of its operation, which inherently includes non-sinusoidal components that produce higher-order harmonics. This highlights the importance of accurate spectral analysis to correctly interpret the dynamics of multi-cylinder engines.

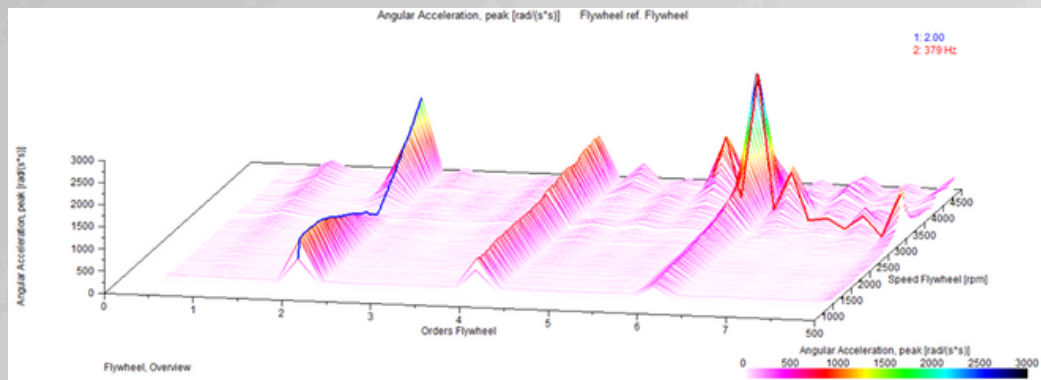


Figure 4 - Order analysis: Waterfall diagram

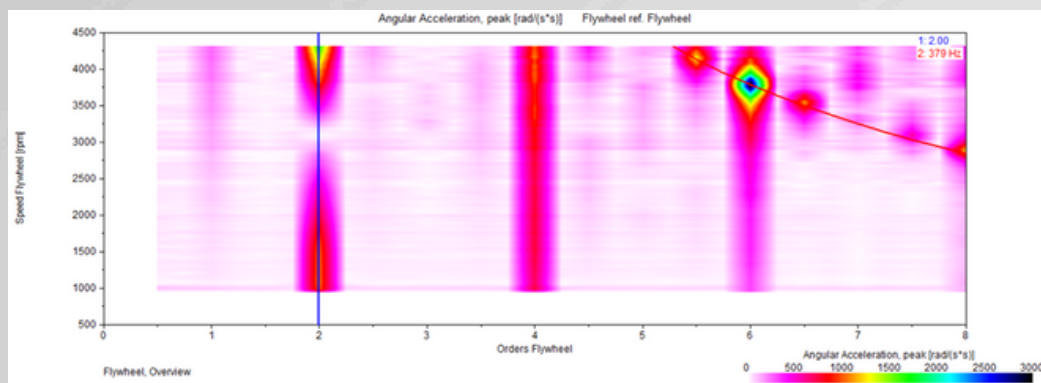


Figure 5 - Order analysis: Countour diagram

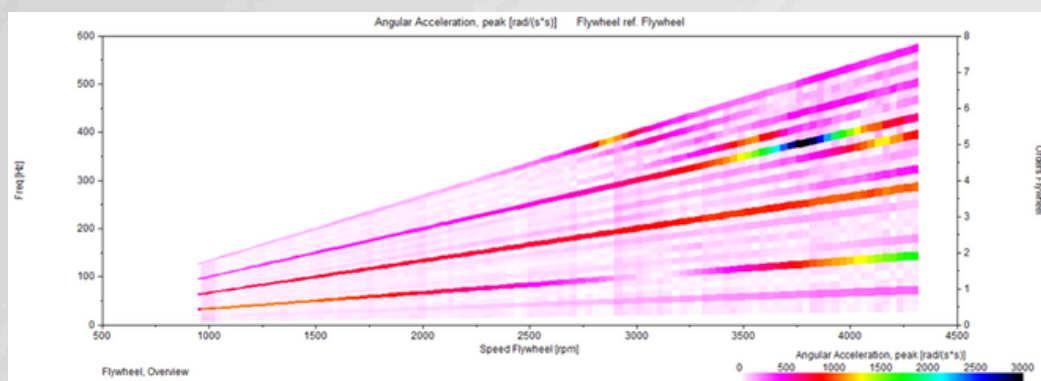


Figure 6 - Order analysis: Campbell diagram

Higher torsional orders may indicate harmonic vibrations or issues in specific components like the drivetrain. By analyzing these orders, engineers can pinpoint which components contribute most to torsional vibrations and take targeted actions to reduce them, ensuring optimal machine performance and longevity.

Torsional Orders in NVH Analysis

NVH (Noise, Vibration, and Harshness) analysis is essential in automotive and industrial applications, where understanding the source of vibration and noise is critical for system optimization. Torsional orders are particularly useful in NVH analysis because they provide a way to relate rotational vibrations to acoustic and mechanical outputs, like noise and vibration. Identifying which torsional orders contribute to excessive noise or vibration helps engineers isolate problematic frequencies. This process enables targeted interventions, such as adding dampers or balancing components, to mitigate vibration, enhance user comfort, and improve overall system reliability and efficiency.

$$\text{Frequency (Hz)} = \frac{\text{Order\#} \times \text{RPM}}{60}$$

Figure 7 - Frequency / Order Formula

How Torsional Orders are Calculated

Torsional orders are calculated by dividing the frequency of a particular vibration event by the fundamental rotational frequency (RPM). For example, if a shaft is spinning at 600 RPM (10 Hz) and a vibration occurs at 20 Hz, this would be considered a second-order torsional vibration.

$$\frac{600 \text{ rev}}{\text{minute}} \times \frac{1 \text{ minute}}{60 \text{ seconds}} = \frac{10 \text{ rev}}{\text{second}} = 10 \text{ Hz}$$

Figure 8 - Example calculation

These orders help engineers correlate specific vibration phenomena with rotational speeds, allowing for more accurate diagnostics. Calculating torsional orders requires precise data acquisition and the use of software that can analyze the frequency spectrum and order of each vibration event relative to the fundamental frequency. Left: Frequency is events per second. Right: Order is event per revolution. For example, if an engine has a 2nd order vibration at 600 rpm, the frequency of vibration is 20 Hz.

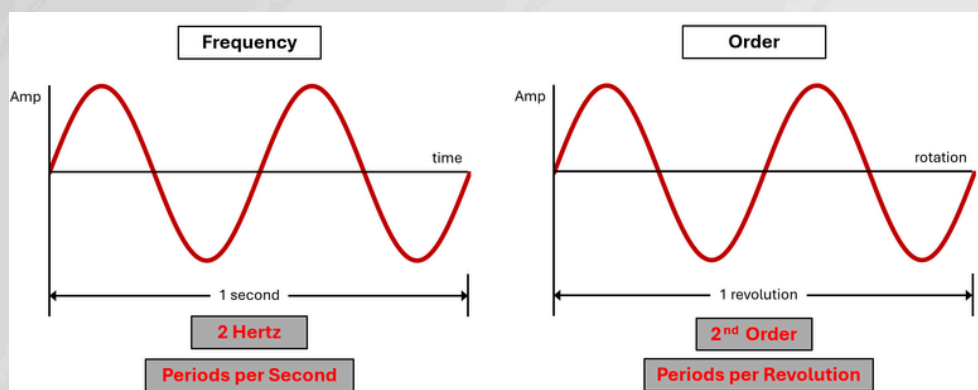


Figure 9 - Visualization Frequency / Order

Torsional Resonance and its Effects

Torsional resonance occurs when the natural frequency of a system coincides with an external driving frequency, leading to amplified oscillations. In rotating machinery, this resonance can cause significant increases in torsional vibration, potentially resulting in catastrophic failure if left unchecked. For example, in engines, crankshaft resonance might occur at a specific RPM, causing the crankshaft to twist excessively, amplifying vibrations throughout the system. Identifying and avoiding resonance conditions through careful design and tuning is critical for the longevity of mechanical systems.

Methods to Reduce Torsional Vibration

To reduce torsional vibration, several methods can be applied, depending on the specific application. Balancing of rotating components helps minimize unbalanced forces that contribute to vibration. Tuning engine parameters or transmission systems to optimize performance and reduce irregular torque pulses can also be effective. Additionally, isolation techniques such as the use of dampers, flexible couplings, or rubber mounts help absorb vibration and reduce transmission to other components. Matching the natural frequency of components to avoid resonance and active vibration control systems, where sensors and actuators work to counteract vibration in real-time, are advanced solutions used in modern systems.

Conclusion

Torsional vibration measurement is a vital component in the design, operation, and maintenance of rotating machinery. By understanding the underlying causes of torsional vibration and utilizing advanced measurement techniques, engineers can prevent system failures, enhance performance, and improve overall system durability. High PPR sensors, accurate torsional order analysis, and mitigation techniques like balancing and damping are essential tools in this process. Whether in automotive engines, industrial turbines, or electric motors, effective torsional vibration management helps extend the operational lifespan of components and ensures smooth, efficient operation across a wide range of applications.

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