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Torsional Vibration Analysis for Rotodynamic Machines : A Comprehensive Approach

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Abstract

Torsional vibration poses significant risks for users of turbomachinery, as it can lead to severe damage to shafts, gear teeth, or couplings. Early detection of these failures is challenging, highlighting the importance of a thorough torsional vibration analysis in turbomachinery design. This paper reviews practical design approaches to ensure systems can effectively address torsional vibration issues. While identifying natural frequencies is usually feasible, accurately predicting torsional vibration problems based on this information is challenging. This paper focuses on post-natural frequency analysis steps, briefly discussing methods like Holzer's method for determining natural frequencies and mode shapes, with detailed treatments available in existing literature. The paper then explores the creation of interference or Campbell diagrams, emphasizing the need to understand excitation frequencies from sources like gears, vaned impellers, and electric motors. Unique challenges related to synchronous motor-driven systems are also addressed. Once interference points are identified, users have two options: modify designs to eliminate interferences or subject the points to further analysis. The paper recommends analyzing all interference points before considering costly design changes. It suggests methods, such as examining mode shapes or torque vs. speed curves, to eliminate non-critical interference points. For remaining points, a damped forced vibration analysis is recommended, with guidelines provided for various machinery classes. Practical solutions are proposed for identified problem areas. Finally, key analysis procedures applicable to most turbomachinery systems are discussed, highlighting their practical applications.

Keywords: *Torsional vibration, Shaft failure, Natural frequencies, Holzer's method, Damped forced vibration analysis.*

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1. Introduction

Ensuring the operational integrity of industrial machinery is crucial for extending the lifespan and efficiency of centrifugal pump systems. Torsional vibration control is a key concern, posing a significant threat to machinery performance and durability [1]. Torsional vibration refers to the angular oscillations experienced by an object, like a shaft, along its rotational axis. Uncontrolled torsional vibration can lead to system failures, especially in power transmission setups with rotating shafts or couplings. Internal combustion engines, for example, can experience substantial resonant reactions, resulting in angular oscillations in the crankshaft [2]. Torsional Vibration Control (TVC) is essential for each unique driveline configuration, such as an engine and an alternator within a generating set [3]. TVC aims to regulate angular vibrations within acceptable thresholds to prevent damage, minimize noise, enhance performance, prevent transmission of vibrations to other parts, ensure compatibility between components, and avoid adverse effects on engine governing and control functions [4].

Modelling reciprocating engines, which produce power through cyclic pulses, requires considering significant resonant reactions. Most crankshafts lack the rigidity to be considered as a single rigid body, even without significant resonant behaviours. Therefore, it's common to simulate a crankshaft and alternator with a certain level of torsional flexibility using a mass-elastic model, representing a series of rigid bodies connected by torsional springs [5]. Obtaining essential data for conducting this analysis, such as mass elastic information, drawings, component limits and fits, and torque transmission limits, from each component manufacturer is crucial before initiating TVC [6].

1. **The TVC process involves several stages:**

1. TVC Calculations and Results Analysis [7]:

- Hand calculations and software tools like MATLAB, FEA, and dedicated TVC software are used to evaluate the system, compare various alternatives, and visualize outcomes across diverse operating conditions. Variations in engine configuration and firing sequences impact different cylinder firing orders distinctly, thereby affecting cycle-to-cycle variations.
- Validation through testing is essential for all torsional vibration calculations, yielding results encompassing angular displacements, accelerations, vibratory torques, stresses at various shaft sections, torsional modes of vibration (natural and forced frequencies), and the heat load in the damper.

2. TVC Procedures:

- Calculate the torsional natural frequencies and mode shapes of the system. - Conduct a forced response analysis, generating the forcing function using cylinder pressures and slider crank parameters to calculate the cylinder's excitation torque.
- Solve the differential equation representing the dynamic characteristics of mechanical vibrations within the system.
- If the TVC fails to meet any pass/fail criteria, communicate the results to the component manufacturers for further assessment and review [8]. The outcome of the analysis is visually depicted in a graph, as indicated in Figure 1.

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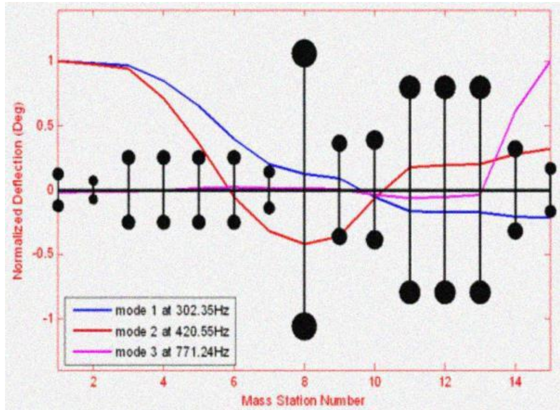

Figure 1. example of the outcome of analysis

Rotating machinery, such as steam turbines, compressors, and generators, often experience increased dynamic stresses near their natural frequencies during torsional vibration. Prolonged operation under these conditions can lead to premature fatigue failure of system components. Detecting torsional vibration in machinery is challenging as these oscillations are not easily detectable without specialized equipment. However, predicting the torsional natural frequencies of a system and implementing design modifications to avoid these frequencies within the machinery's operating speed range are crucial. Torsional vibrations can induce stress reversals, causing metal fatigue and impacting gear teeth. Elements like flywheels, parts of flexible couplings, and turning disks are typically treated as rigid disks with easily determinable mass moments of inertia. Flexible couplings and slender shafts with small polar mass moments of inertia are often regarded as massless shafts with readily calculable torsional stiffness. For shafts with larger diameters where inertia cannot be neglected, approaches include dividing the shaft into numerous sections and aggregating the inertia of each section as a rigid disk while maintaining the shaft's elasticity as a massless torsional shaft, or considering distributed inertia and stiffness across sections in cases where the shaft diameter is substantial. Thus, the system simplifies into interconnected rigid disks through massless elastic shafts or distributed mass and elastic shafts. When parts of the system are interconnected via gears, the system's inertias and stiffnesses need to be recalibrated to a reference speed. This review paper aims to cover the methods and analysis used in the literature for torsional vibration in centrifugal pumps. The paper seeks to:

- **Summarize Key Concepts:** Present and clarify fundamental concepts and definitions related to torsional vibration, including the mechanisms, causes, and effects of torsional vibrations in mechanical systems.

- **Review Methodologies:** Examine various analytical and experimental methodologies used for assessing and studying torsional vibrations, including their strengths, limitations, and applications.

- **Evaluate Control Strategies:** Review existing control methods and strategies designed to mitigate the adverse effects of torsional vibrations and assess their effectiveness.

3. Literature review

This section aims to consolidate prior research efforts, primarily focused on Torsional Vibration Analysis (TVA) concerning centrifugal pumps, driven by AC motors or Diesel engines, providing a foundational understanding of this domain.

a) Torsional Vibration Mitigation Techniques:

Chen, Xu, and Wenske [9] introduced a model-based active damper to mitigate torsional vibration using the linear-quadratic- Gaussian (LQG) algorithm. This approach accounts for rotor blade flexibility in the drive train and employs a three-mass model for accurate representation. The study utilizes simulation tools like FAST and MATLAB /Simulink to comprehensively describe mechanical and electrical dynamics. The simulations analyze

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drive train vibrations and evaluate the algorithm's effectiveness, showing efficient suppression of torsional vibrations even during grid faults.

Gao, et al. [10] introduced a novel torsional vibration absorber featuring a magnetorheological elastomer (MRE) as its intelligent control component. Their study focused on modal analysis, frequency-tracking methods, and damping properties. A transient dynamic simulation validated the mechanical structure's validity, ensuring a match of magnetic field parameters. Magnetic circuit simulations and magnetic field supply analyses validated a closed magnetic circuit. A prototype of the vibration absorber was developed, with Gauss meter tests verifying the absorber's magnetic field strength. A specialized test apparatus employing a torsional vibration exciter conducted comparative experiments, validating frequency shift traits and confirming the vibration reduction achieved by this innovative MRE torsional vibration absorber.

b) Dynamic Modeling and Simulation Studies:

Matyja and Łazarz [11] presented a Simulink block library that models coupled flexural, torsional, and longitudinal vibrations during machine startup, offering a more efficient description of motion with reduced simulation times.

Zhou, et al. [12] constructed a dynamic model for high- speed centrifugal pumps, incorporating nonlinear factors affecting gear pairs, bearings, and seals. The investigation delved into stability and vibration responses across different gear transmission ratios, highlighting the influence of distinct frequencies on gear vibrations and the importance of deliberate design considerations for transmission ratios in these pumps.

c) Machine Design and Optimization:

Corbo, and Melanoski [13] aimed to offer users a practical design method to avoid significant issues during operations. Their focus was on outlining the necessary steps following the identification of natural frequencies.

Nassar and Yaseen [14] showcased the practicality and utility of a modified approach along with a MATLAB Graphical User Interface (GUI) to assess the impact of torsional vibration on established rotor control techniques to enhance system reliability and performance. The integration of advanced modeling and simulation techniques, along with experimental validation, has proven essential for accurate vibration analysis.

Furthermore, the adoption of innovative approaches, such as adaptive control strategies and real-time monitoring, has shown considerable promise in improving the dynamic performance and safety of mechanical systems. By addressing both theoretical and practical aspects of torsional vibration, this review provides a holistic understanding of the challenges and solutions in the field.

Moreover, it emphasizes the importance of interdisciplinary collaboration and continuous research efforts to drive systems like two, three, and five rotor configurations. Their refined approach and GUI serve as highly beneficial tools for engineers, designers, and analysts dealing with vibration challenges in rotor systems.

Li, et al. [15] employed a numerical method to compute the natural modes of a pump turbine runner in both air and flow channels, investigating the impact and mechanism of outer edge modifications on the runner's natural frequencies.

d) Energy Harvesting from Mechanical Vibrations:

Yatim, et al. [16] introduced a model for converting mechanical vibrations into electrical energy using a piezoelectric converter. They developed the model based on the characteristics of the PI P-876 piezoelectric model and utilized a non- adaptive rectifier circuit to facilitate direct voltage conversion, yielding energy suitable for small home appliances and low-powered wireless sensor networks.

f) Advanced Manufacturing Techniques:

Patel, et al. [17] investigated Wire Electrical Discharge Machining (WEDM) and its effects on material removal.

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4. Conclusion

In conclusion, torsional vibration analysis is pivotal in understanding and mitigating vibration issues in mechanical systems, particularly in multistage centrifugal pumps. This comprehensive review has highlighted the significance of identifying critical frequencies and vibration modes and developing efficient advancements in torsional vibration analysis. Such efforts are crucial for optimizing the design and operational stability of various industrial applications, ensuring long-term efficiency, and resilience against torsional vibrations. This review serves as a valuable resource for researchers, engineers, and practitioners, offering insights and guidance for future developments in the field.

5. Future Work

- **Diesel Engine Interaction**:

Investigate the interaction between torsional vibrations and diesel engine dynamics, focusing on how engine load variations affect pump performance.

- **Adaptive Control Systems**:

Develop adaptive control systems specifically designed for pumps driven by diesel engines, optimizing for varying operational conditions.

- **Hybrid Modelling Techniques**:

Employ hybrid modelling techniques combining computational fluid dynamics (CFD) and finite element analysis (FEA) to accurately simulate the coupled behaviour of diesel engines and pumps.

- **Experimental Validation**:

Conduct extensive field experiments to validate theoretical models and control strategies, ensuring practical applicability and reliability.

- **Vibration Damping Materials**:

Explore the use of advanced damping materials and techniques to reduce the impact of torsional vibrations in pumps driven by diesel engines.

- **Energy Efficiency Optimization**:

Investigate methods to enhance the overall energy efficiency of the system, considering the fuel consumption and vibration control mechanisms.

- **Predictive Maintenance**:

Implement predictive maintenance frameworks utilizing real-time data from sensors to anticipate and address torsional vibration issues before they lead to system failures

- These steps can optimize the pump system for long-term reliability, efficiency, and safety.

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