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Torque Evaluation of Automotive Connecting-Rod Bolts Using Piezoelectric Sensors and Contact Acoustic Nonlinearity Methods

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1 Abstract

This work presents a nonlinear ultrasonic Structural Health Monitoring (SHM) approach for the non-destructive assessment of bolt torque in connecting rod assemblies.

Variations in preload are captured through changes in higher harmonic components generated by Contact Acoustic Nonlinearity (CAN), which proved sensitive to different torque levels, excitation frequencies, and bio lubricants.

The results demonstrate that nonlinear ultrasonic indicators offer a reliable basis for real-time monitoring of bolt tension in safety-critical mechanical joints.

Keywords: nonlinear ultrasonics; structural health monitoring; bolt torque; bio lubricants; contact acoustic nonlinearity.

2 Introduction

Bolted joints are critical to the structural integrity of connecting rods, where maintaining a stable preload is essential for reliable load transfer and strength under dynamic operating conditions. Preload degradation due to vibration and thermal effects can compromise joint integrity, making early detection of bolt loosening a key requirement for effective SHM in safety-critical systems [1].

Conventional preload assessment methods, including conventional ultrasound-based techniques, rely on indirect indicators and bulky instrumentation that cannot be easily integrated for continuous, in-service monitoring, thus failing to meet SHM requirements [2–5].

Nonlinear ultrasonic techniques based on CAN overcome these limitations by exploiting harmonic and combinational frequency generation at imperfect interfaces, which has been shown to correlate strongly with bolt preload conditions [2–5]. In this context, the present work proposes a nonlinear ultrasonic SHM approach for non-destructive bolt torque evaluation in a steel connecting rod assembly, also assessing the influence of excitation frequency and bio lubricants to improve monitoring robustness.

3 Material and methods

The experimental investigation of CAN was conducted using a through-transmission ultrasonic setup, with two small (5 mm) piezoelectric transducers (PZT) acting as emitter and receiver and bonded to the bolted assembly.

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A sinusoidal burst excitation was generated by a Keysight 83920A waveform generator, amplified, and transmitted to the structure, while the received response was acquired using a high-resolution digital oscilloscope and a Picoscope 4262 for frequency-domain analysis.

Bolt preload was controlled using a digital torque wrench with ±2% accuracy, enabling repeatable correlation between nonlinear ultrasonic indicators and torque levels.

The excitation frequency was varied between 10 and 100 kHz, and the identified resonance frequencies were confirmed using a single-point Laser Doppler Vibrometer (LDV). Measurements were conducted under two lubrication conditions: a conventional mineral grease and a sustainable bio lubricant obtained from hydrogenated waste cooking oil (WCO), allowing evaluation of lubricant-dependent interfacial nonlinear behaviour.

4 Results and discussion

The results are presented in terms of the nonlinear parameters β and δ_1 as functions of the normalized tightening torque for the two lubrication conditions considered. The excitation frequencies were selected through dedicated narrowband frequency sweep procedures, which allowed identification of the frequencies most sensitive to nonlinear effects.

For the mineral grease condition, the strongest and most consistent inverse correlation between the nonlinear indicators and torque was observed at 18.3 kHz, where both β and δ_1 decrease monotonically with increasing tightening. In contrast, when the hydrogenated WCO was used as a bio lubricant, the most sensitive response was obtained at 41.3 kHz, again showing a clear reduction of nonlinear features with increasing torque (Figure 1).

These results confirm the frequency-selective nature of nonlinear ultrasonic techniques and demonstrate that the lubrication condition significantly influences the activation of nonlinear resonances relevant to bolt preload assessment.

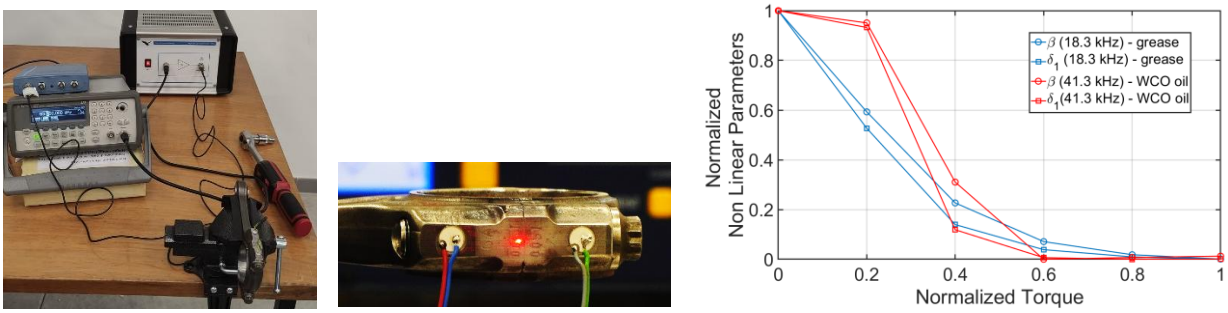

Figure 1. Set-up with a zoom showing the position of PZT sensors and correlation between nonlinear indicators β and δ_1 and normalized torque for the two lubricants.

5 Conclusions

This study demonstrates that nonlinear ultrasonic techniques based on CAN provide a sensitive and non-invasive approach for monitoring bolt preload in connecting rod assemblies, highlighting the strong influence of excitation frequency and lubrication conditions and confirming their potential for reliable, in-service SHM of safety-critical bolted joints.

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