Thermo-Elastic-Plastic Behaviors of Vibro-Acoustically Modulated Interfacial Waves in Bolted Joint and Its Application in Monitoring of Early Bolt Loosening

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ABSTRACT

The non-monotonic variation of nonlinear intensity of vibro-acoustic modulation (VAM) during the evolution of contact-type damage has been well observed. To enhance the detectability of modulated waves for bolt loosening, a method, which ingeniously makes use of the thermo-elastic-plastic susceptibility of the modulated waves under varying temperatures, is developed, referred to as thermally interfered vibro-acoustic modulation (TI-VAM). The level of the acoustic nonlinearity in the fully tightened joint can be enhanced under higher temperatures and that in low-stress preload can be enhanced under lower temperatures. The nonlinear response from bolt loosening dominates over material nonlinearity, ensuring the sensitivity of TI-VAM in practical applications. With such merit, this method can improve the monitoring of early bolt loosening or detecting other contact-type damage.

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INTRODUCTION

Bolt loosening poses a critical threat to bolted structure safety, as rapid loosening can trigger catastrophic failures [1]. Studies indicate [2, 3] that interfacial contact degradation induces significant changes in contact acoustic nonlinearity (CAN), providing a theoretical foundation for monitoring bolt loosening via nonlinear acoustic features [4, 5].

The vibro-acoustic modulation (VAM) technique caused by CAN has been widely used to evaluate bolt loosening. Amerini *et al.* [6] validated the correlation between modulation indices and residual torque. Zhang *et al.* [7] established theoretical relationships using interfacial stiffness models. Gong *et al.* [8] improved accuracy through higher-order sideband analysis. Zhao *et al.* [9] enhanced applicability in complex structures via frequency-swept excitations and bispectral energy.

Notably, temperature effects significantly interfere with VAM detection. Experiments [10, 11] confirm that damaged specimens exhibit markedly higher temperature sensitivity in modulation indices compared to intact ones. However, dynamic coupling between preload and thermal stress [12, 13] complicates quantitative temperature compensation. Current research lacks systematic exploration of temperature effect on modulated waves during bolt loosening detection, representing a major bottleneck in engineering applications.

In this study, VAM experiment was conducted under temperature changes to reveal the behavior of the modulated features affected by the interfacial thermal-elastic-plastic coupling of the bolted joint. Furthermore, the major and minor nonlinearities under the effect of temperature changes were discussed in the final section.

EXPERIMENT

The bolted joint made by carbon fiber reinforced polymer plates was tightened to the target preload using a torque wrench. Thermal interference was then induced through a temperature chamber (Figure 1). Post-temperature stabilization, high-frequency at 29800 Hz and low-frequency at 450 Hz signals were generated via a waveform generator, then applied to the specimen through piezoelectric actuators. The superimposed TI-VAM wavefield, generated through nonlinear interactions at the bolted interface under temperature control, was acquired by a surface-attached accelerometer. Signal acquisition was conducted via an oscilloscope at 250 kHz sampling frequency.

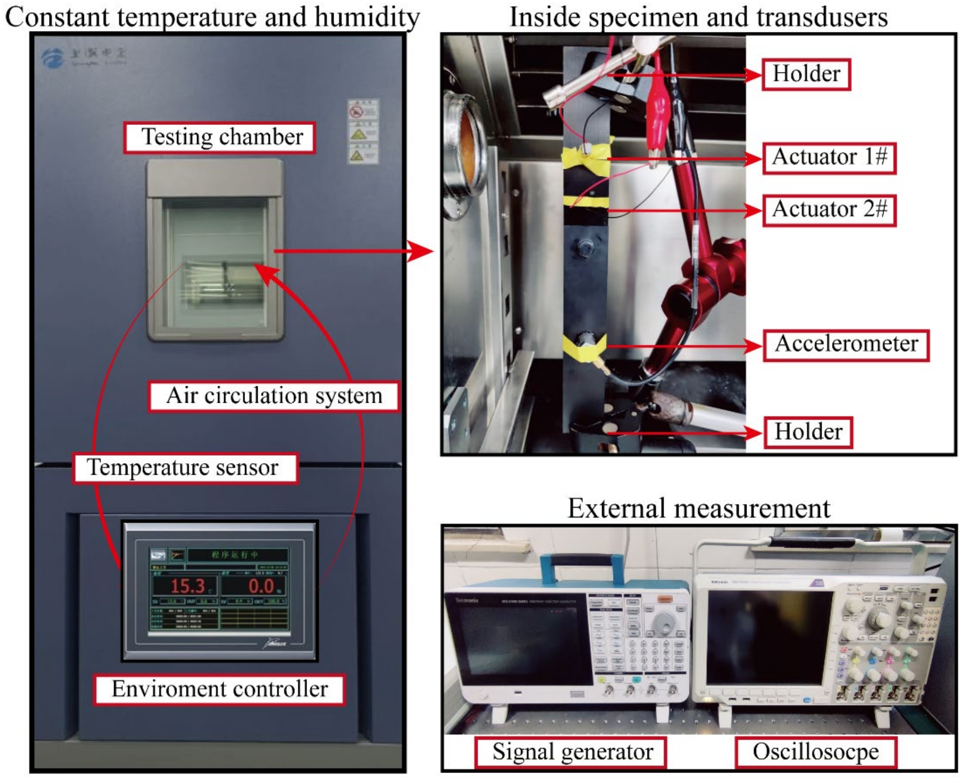


Figure 1. Experimental setup.

Figure 2 shows the modulation index, calculated as the magnitude ratio of sidebands to the fundamental waves. The enhancement and suppression of sideband amplitudes in TI-VAM via the thermal interference ultimately achieve monotonicity control of the modulation index curve. At 20°C, the modulation index decreases exponentially with increasing preload but manifests insensitive to changes in the high-stress range of 10 to 16 N·m. With increasing temperature, thermal stress at the interface causes significant nonlinear thermo-elastic-plastic modulation responses, which is reflected in the gradual shift of β (modulation index) toward lower stress levels. For example, the lowest vertex on the β-curve shifts from 16 N·m at 20°C to 14 N·m at 30°C and further to 12 N·m at 40°C. However, such variation is not a proportional behavior, when the temperature rises to 60°C, the modulation index of the TI-VAM method drastically shows the most significant variation of 2.5 V^{-1} for a loosening range of 16 to 14 N·m (by 12%), which is much higher than the nearly unchanged results observed at 20°C. In contrast to the heating treatment, cooling the joint from 20 to 10°C shifts β to the high-preload direction, as the cooling method reduces the number of rough asperities in contact and leads to more active boundary opening and closing in the bolted region. The cooling process can also be beneficial to enhance the sensitivity of modulation index for a lower-stress preload stage in the loosening detection.

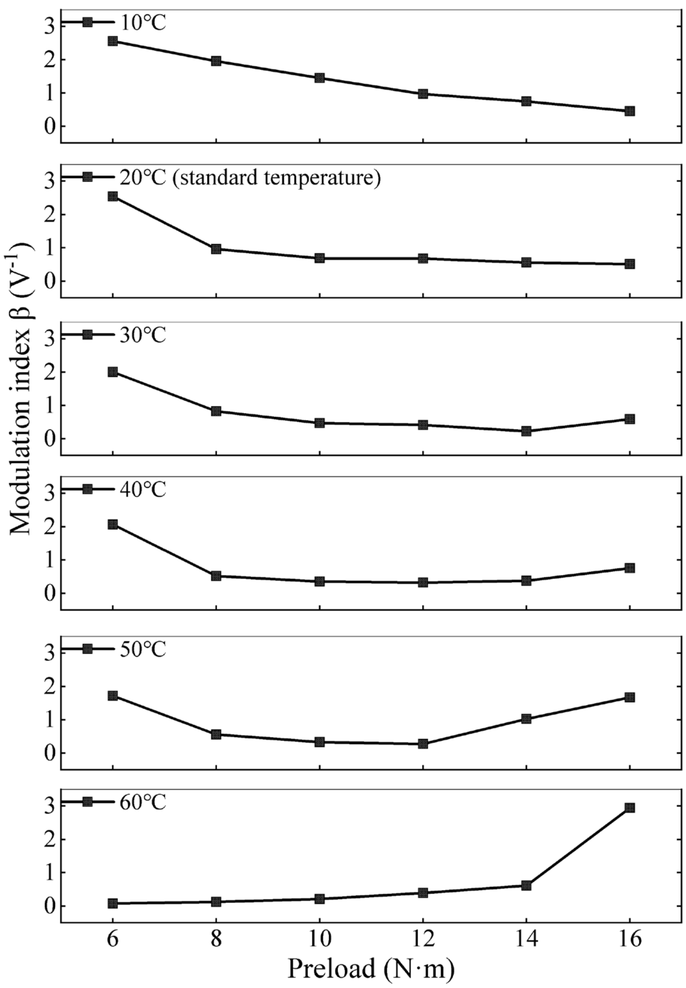


Figure 2. Measured modulation index β.

DISCUSSION

To isolate the contributions of material nonlinearity and bolt-nut contact nonlinearity in the TI-VAM detection, three connection configurations were designed (as shown in Figure 3). Case I: The bolt and plates were entirely bonded together using high-temperature-resistant adhesive, ensuring only material nonlinearity can cause modulation responses while eliminating contact nonlinearity. Case II: A rotatable nut was added to the bonded specimen (Case I) to introduce bolt preload, thereby incorporating contact nonlinearity between bolt and nut. Case III: The reference case, same as the normal experimental setup in Figure 2 and including all the nonlinear sources causing modulation responses. In Figure 4a, the orange line represented the TI-VAM feature caused by material nonlinearity under thermal interference (Case I), while the dark lines were the reference for normal bolted joint in Case III. The material nonlinearity increased with rising temperature because the potential of particles in the structure became larger [11]. However, the contribution of thermal-interfered material nonlinearity to the TI-VAM response is slight compared to the contact nonlinearity between plates. The modulation index in Case I was enhanced by only 0.1 V^{-1} from 20

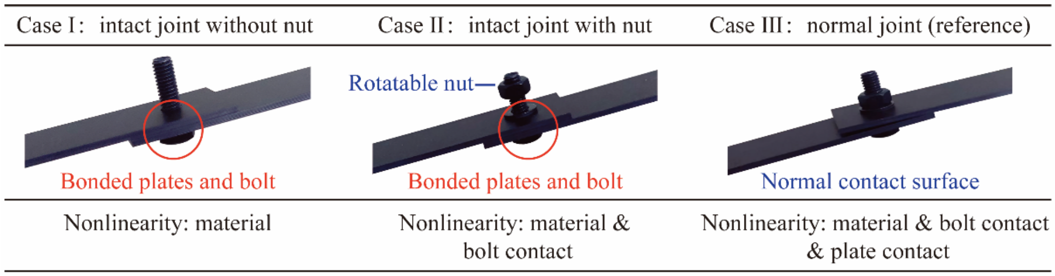


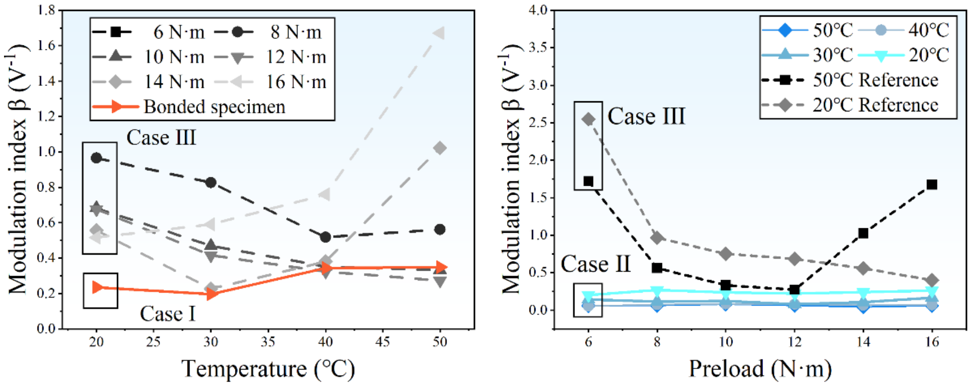
Figure 3. Arrangement of the joint connected by different forms

to 50°C, which only matched to that in Case III at 14 N·m from 30 to 40°C. Hence, for the investigated conditions (preload and temperature), the theoretical assumption of neglecting the contribution of temperature-induced material nonlinearity can be reasonable. We should mention that the material nonlinearity affected by thermal interference may still become a vital source of nonlinear TI-VAM responses under extreme conditions, *e.g.,* glass transition temperature.

In Figure 4b, the blue lines represented β caused by material nonlinearity and bolt-nut contact nonlinearity for Case II, while the dark lines showed the reference (Case III). When introducing the contact force between the nut and the bolt, the material thermal expansion of the specimen was constrained. Thus, the increase of β in Case I was taken place in Case II by the decrease of β caused by the thermal-interfered bolt-nut contact nonlinearity. However, such variation of modulation index affected by temperature change was only $0.2V^{-1}$, still much lower than that in Case III. In addition, β in Case II caused by bolt-nut contact did not vary like that in Case III during the preload variation, indicating that the plate-plate contact in the TI-VAM detection on the bolt loosening was the dominant over the bolt-nut contact.

CONCLUSION

The nonlinear behavior of vibro-acoustic modulation becomes unstable and less sensitive when detecting micro-loosening of bolts under rigid preload conditions due to the complex thermo-elastic-plastic wave-interface interaction. To improve the precision of early detection of bolt loosening, this study proposes a new method, termed thermal-interfered vibro-acoustic modulation (TI-VAM). Instead of filtering out the thermal effect during signal processing, this method actively leverages the thermal influence on interfacial acoustic modulation to control the intensity and monotonicity of modulation features during detection. As the temperature rises, the modulation index shows a monotonic behavior during the early loosening stage, reducing misjudgment risks. Additionally, the modulation index for low-stress stage can be also enhanced under cold environments. Experiments highlight that the nonlinear response from bolt loosening dominates over material nonlinearity, ensuring the sensitivity of TI-VAM in practical applications.



(a) case I (b) case II

Figure 4. Measured modulation index introduced by different nonlinearities

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