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Estimating bolt tightness from measured vibrations: Effective linearity of nonlinear boundary stiffness

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Abstract. Experimental evidence shows that the tightness of a bolt can be estimated from its vibrational response using a pre-stressed beam model with linear stiffness at its boundaries. We show how considering only linear boundary stiffness successfully reproduce the experimental results. A model of multiple nonlinear springs, modelling the asperities, is presented and it is shown that as the number of asperities increases the system's response becomes linear-like.

Introduction

Structural health monitoring techniques based on vibration measurements have been receiving large attention in the last decades, including techniques for estimating bolted joints tightness and detecting loosened bolts. Due to the exposure of bolted joints to external forces, the bolts may loosen and therefore affect the healthy functioning of the bolted structure.

A technique has been proposed to assess the level of bolt tightness and to quantify the tension based on measured natural frequencies and damping ratios of the bolt [1,2,3]. This technique is investigated experimentally and theoretically. The experimental results are explained using a simple model for the bolt that consists of a pre-stressed beam with linear stiffness at its boundaries. In the present work we consider a system of multiple nonlinear springs that model the multiple asperities in the boundary contact surface and we show that as the number of asperities increases the boundary stiffness becomes effectively linear.

Analysis

Figure 1 shows the first bending natural frequency for a bolt as function of bolt tension. At low tension the natural frequency changes nonlinearly with tension. As the bolt is gradually tightened the frequency starts changing more linearly with tension.

The good agreement between the theoretical results (solid line), obtained from the mathematical linear model, and the experimental results (markers) indicates that the boundary stiffness is important for the transverse frequency trends, and thus for the possibility of quantifying bolt tension by the proposed beam model. It also indicates that considering linear boundaries in the beam model is sufficient to excellently reproduce the experimental data.

In reality the boundary stiffness is known to be locally (micro-scale level) nonlinear. However, as described above, with only linear boundaries the theoretical beam model can explain experimental data. In this work an attempt is made to explain this phenomenon by considering a system of multiple chains, where each chain is connected to a common base by a nonlinear spring while the other ends are preloaded, with one preloaded end subjected to an impact. Each nonlinear spring models the nonlinear stiffness for a single material asperity. The multi-degree of freedom system is then reduced to a first-mode equivalent single-degree freedom spring-mass system. The restoring force of the spring has a linear and correction part representing effective stiffness in the original multi-degree of freedom system. The model reduction is performed by numerically simulating the response of a mass of one of the chains, and then solving for the forcing part representing the correction to the single-mode restoring force.

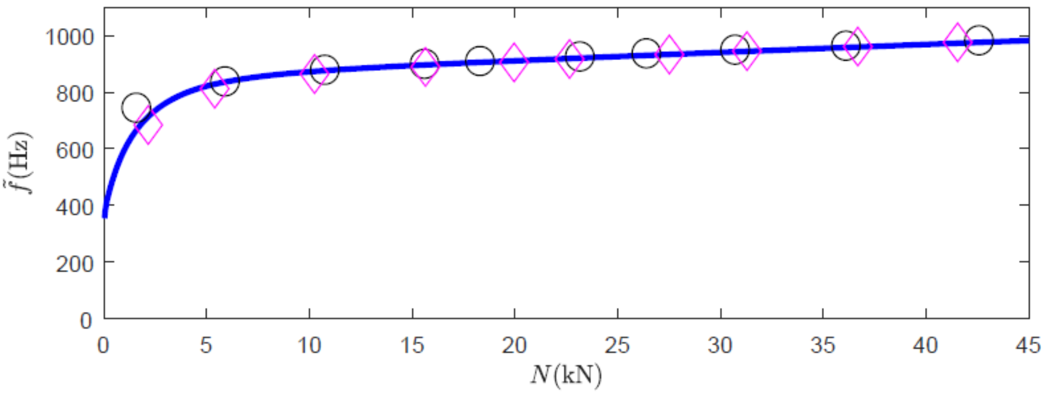

Figure 1: First transverse frequency of a bolt M12x260 as function of bolt tension. Solid line/markers: Theoretical/experimental results (adapted from [1]).

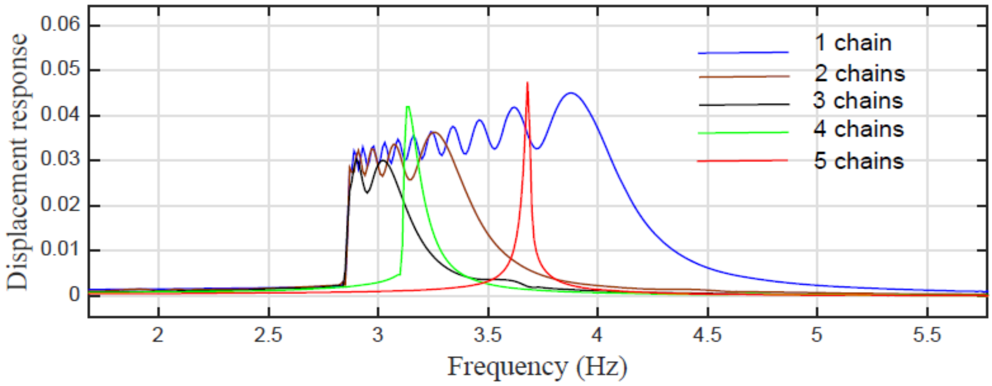

Figure 2: Fourier transform of the displacement impact response of the system for different numbers of chains.

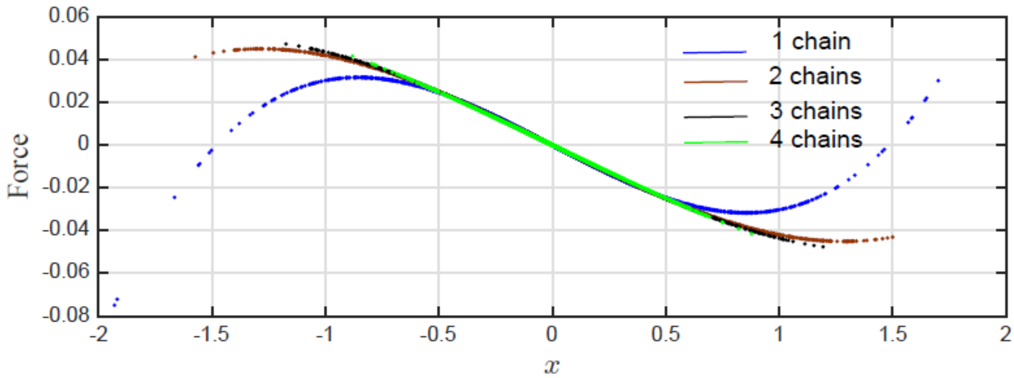

Figure 3: Correction part of the restoring force in the single-degree freedom spring-mass system.

Figure 2 shows the Fourier transform of the system response to an impact of one mass as the number of asperities/chains increases. As the number of asperities increases, the response curve becomes narrower with a clear dominant peak. When there is only one chain, the response contains different frequencies, while in the case of 5 chains the response has a single frequency. This indicates that as the number of asperities is increased the response becomes more linear. Figure 3 shows the force ¨correction¨ to the effective restoring force as a function of displacement, as the number of asperities/chains is increased; the corrections has a negative slope/stiffness near zero, corresponding to the softening effect of the serial arrangement of chain springs. As appears the range of linear behavior of the correction increases with the number of chains. Thus the contact with a larger number of chains/asperities can be modeled as a linear, this may contribute to explain why linear boundary stiffness appears sufficient for modelling boundaries in a tightened bolt.

Conclusions

Tightened bolts can be successfully modeled as a pre-stressed beam with *linear* boundary stiffness. In this work we showed, using a system of multiple nonlinear springs, how a collection of multiple asperities, with nonlinear stiffness, reduces to an effective linear stiffness with a linear-like response behavior.

Acknowledgment

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