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Vibration-based testing of bolted joints

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Summary. For many technical installations that are held together by bolted joints (Fig. 1(a,b)), the regular checking and documentation of proper bolt tightness is essential for certification and safe operation. However, with large structures and heavy bolts, the work required for the inspectors can be physically demanding and time consuming, e.g. with heavy hydraulic torque wrenches in demanding environments. In this work we attempt to develop reliable vibration-based techniques for bolt tightness estimation, using advanced mathematical modeling/analysis, and suitable measurement equipment and signal processing.

Introduction

In recent pilot studies we have started investigating how to possibly use measured flexural (i.e. transverse/bending) vibrations, induced by bolt-tapping, to estimate bolt tightness. Some of the vibration features we investigated showed strong correlation with bolt tightness. For example, the lowest natural frequency, as estimated from the vibration signal, is close to being proportional to bolt tension, except at very low tensions (Fig. 1(d)). To obtain an estimate of bolt tightness this way only requires a period of time of the order of a second where the user taps the blot with a light hammer, which triggers measurement and data processing. However, experimental results revealed that this technique encounters two problems, for it to be presently useful in real applications: First the variability in results is too large, about twice that for a torque wrench. Figure 2(a) shows that the slope of the curves varies for separate experiments with similar increasing bolt tension, which suggests that the quantity ω/β is an unreliable feature for estimating bolt tension. A second fundamental problem is that the relative change in natural frequency is approximately proportional not only to bolt tension, but also to slenderness ratio. Thus, if only the natural frequency feature were to be used for estimating bolt tension, accuracy will drop off for the short and thick bolts that are often used in critical joints.

Traditional bolt tightening procedures

Traditional bolt tightening procedures [1] include torque wrenches, elongation measurements (e.g. by LVDT or ultrasonic transducers), and sensor force washers (typically strain gauge based). Various ultrasonic methods and the problems associated with them are overviewed in [2], while the use of changing magnetic permeability for estimating bolt tension is described in [3], and dynamic problems associated with bolts (e.g. loosening) in [4]. Most articles on ultrasonic methods are practically oriented towards measuring techniques, and less towards fundamental theoretical issues of relations between tension and measurable features such as resonance frequencies and wave pulse passage time. The theory used typically involves longitudinal vibrations, not including the flexural vibrations which are of lower in frequency, and at main focus in the current project. Longitudinal resonance frequencies drop with tension due to a combined effect of increased length and reduced longitudinal wave speed; this is utilized in traditional ultrasonic transducer based monitoring of bolt tension. For flexural vibrations, it is well known how tension increase the flexural resonance frequencies , but only little seems reported on using measured flexural resonances for bolt tension monitoring. A number of technical applications based on ultrasonic transducers (pulsed or continuous wave) has been patented but seemingly not on systematic use of measured features of flexural resonances/vibrations.

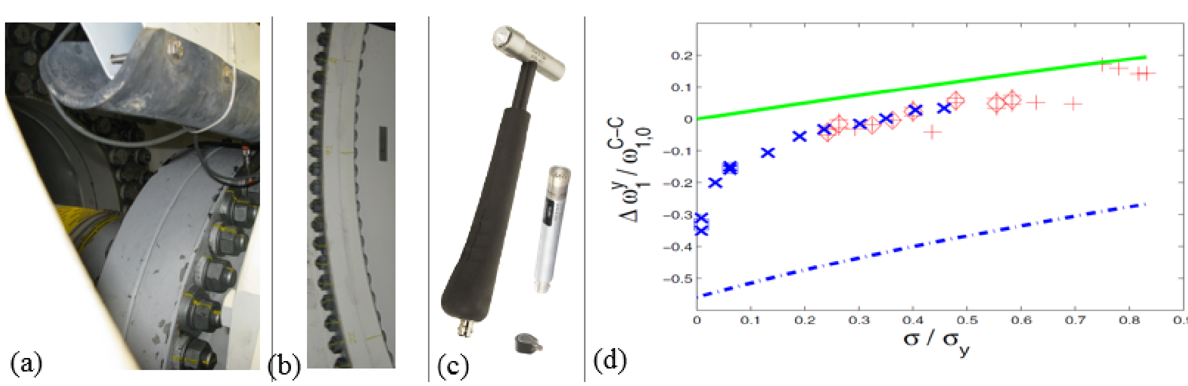

Figure 1: Dense arrays of bolts in (a) a wind turbine main shaft, and (b) a wind turbine tower flange [Brüel & Kjær customer tests]. (c) Impact hammer, microphone, accelerometer. (d) Experimentally measured change in lowest natural frequency for two impacted M12x240 mm bolts vs. normalized bolt tension [MSc thesis (J.S. Knudsen, 2013)]; Symbol markers: results for each bolt using two different ways of determining natural frequency. For higher tension, measurements approach the theoretical prediction (upper line) for a simple Bernoulli-Euler clamped-clamped beam model (lower line for a hinged-hinged beam).

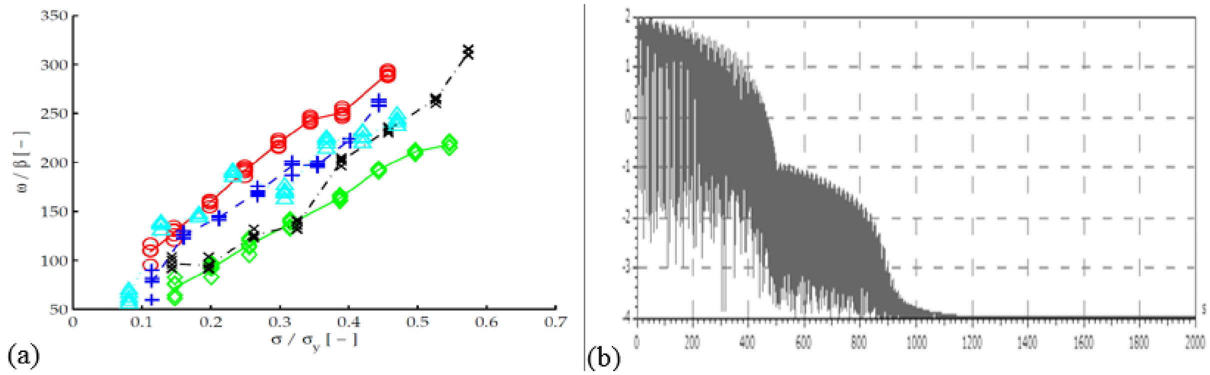

Figure 2: (a) Measured ratio of natural frequency ω to decay rate β for the second flexural vibration mode of an impacted M12x140 mm mm bolt-nut assembly vs. normalized bolt tension [MSc thesis (E. Vind and S. Jespersen, 2014)]; each curve connects averaged experimental measurements as the tension is increased. (b) Numerically simulated response (log(|acceleration|$+10^{-4}$)) vs. time for an impacted bolt joint with an advanced serial/parallel nonlinear friction model; Three markedly different decay envelopes are identified, separating times where the energy dissipation is dominated by, respectively, pure slip friction (initial phase), stick-slip friction (middle phase), and viscous-like (could also be hysteretic) linear damping (final phase).

Bolt tightness indicators

The two fundamental problems mentioned in the introduction call for considering other vibration features as well, maybe in combination. Therefore, to remedy to these shortcomings, we have started investigating additional temporal, spectral, and temporal-spectral features which include *higher natural frequencies*, *attack time*, *equivalent linear decay rates*, *multiphase nonlinear decay rates* (Fig. 2(b)), *ratio of natural frequency to decay rate*, *psychoacoustic measures* (e.g. loudness), *amplitudes of nonlinear higher harmonics*, and (with two-frequency excitation) *amplitudes of nonlinear sidebands* [5, 6, 7].

Alternative bolted joint integrity measures

The variability in measurements might be due to an inherent feature of the traditional way of using torque wrenches for quantifying bolted joint integrity: Torque relates only indirectly to joint tightness, it depends also on other quantities, most importantly friction. To address this fundamental issue, in this work we will consider also new ways of quantifying bolted joint integrity, i.e. how vibrations could be used not just as a substitute for measuring torque, but maybe as a better means.

Conclusions

This is a work in progress; updated results will be orally presented at the conference.

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