Nonlinearity in estimating bolt tension from vibrations

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Summary. Many technical installations are held together by critical bolted joints. A critical bolted joint can have many appearances, from bolted flanges with many bolts to smaller lap-joints with only a few bolts. *Critical* imply that failure is not accepted, as it would lead to dangerous situations and most likely very costly repairs. Such joints are found in wind turbines, pressurized pipelines, large machinery etc. To ensure safe operation, regular checking and documentation of bolt tension is required, which is both costly and time consuming, and traditional tightening techniques are not very accurate. Recent work has shown potential in estimating bolt tension by using vibrations actively. e.g. by analyzing the vibrational response in a bolt after a hammer impact. Tests of this have been carried out with good results for setups with a single bolt. However, most often a bolted joint consists of multiple bolts holding at least two parts together. The more parts and bolts, the more sources to nonlinear effects from frictional contacts and potential vibrational coupling. In this work, we present the current status of the method with new results from a multi-bolt setup, and raise the question of which potential nonlinear effects need to be considered to apply the method more generally for multi-bolt joints.

Introduction

Traditional tightening methods include torque wrenches and hydraulic tensioners [1]. These cannot estimate the tension, so checking is done by retightening. This can lead to overtightening, which can in turn introduce failure. Furthermore, it is time consuming to retighten all bolts, especially if the retightening revealed that only a few bolts were in fact loose. Newer technologies include bolts with incorporated strain gauge sensors, which is more expensive than traditional bolts and potentially fragile, and ultrasonic transducers [2], which measure bolt elongation. These new advances show that it is definitely of interest to improve both speed, cost and accuracy in estimation of bolt tension. Vibrations could be advantageous to use, as control can then be done without employing heavy equipment and there are direct correlations between tension and bending vibrations. The challenge is to ensure that other mechanism that influence the vibrational response have been investigated, so that a vibrational response of any bolt, in any structure, can be analyzed correctly, thus permitting a robust estimation of tension. To get to that point possible nonlinear effects must be understood.

Bolt tightness indicators based on bending vibrations

A bolt can be considered a beam with rotational and translational linear boundary stiffness springs [3], whose stiffness may increase nonlinearly with tension [3]. As a bolt is tightened the boundary stiffness increases, as well as the tension. In [4] demonstrated that a large number of nonlinear boundary micro springs can effectively behave as a linear spring.
Firstly, a bolt can indeed bend as a beam. This is experimentally investigated in [5] by analyzing measurements from a scanning laser Doppler vibrometer and obtaining actual mode shapes. Furthermore, experimental results for a single bolt show that it is possible to get reproducible results of the first and second transverse natural frequency, increasing first strongly with tension and then linearly, as shows in Figure 1(a) from the small color markers [3,6]. A nonlinear stiffness model adapted from [3] can be fitted to the measurements (dashed lines in Figure 1(a)). The corresponding damping ratio decreases with tension, strongly for low tension, and weakly for high tension [3,6]. Combining the information coming from the bolt tightness indicators can provide an estimate of bolt tension [6,7].

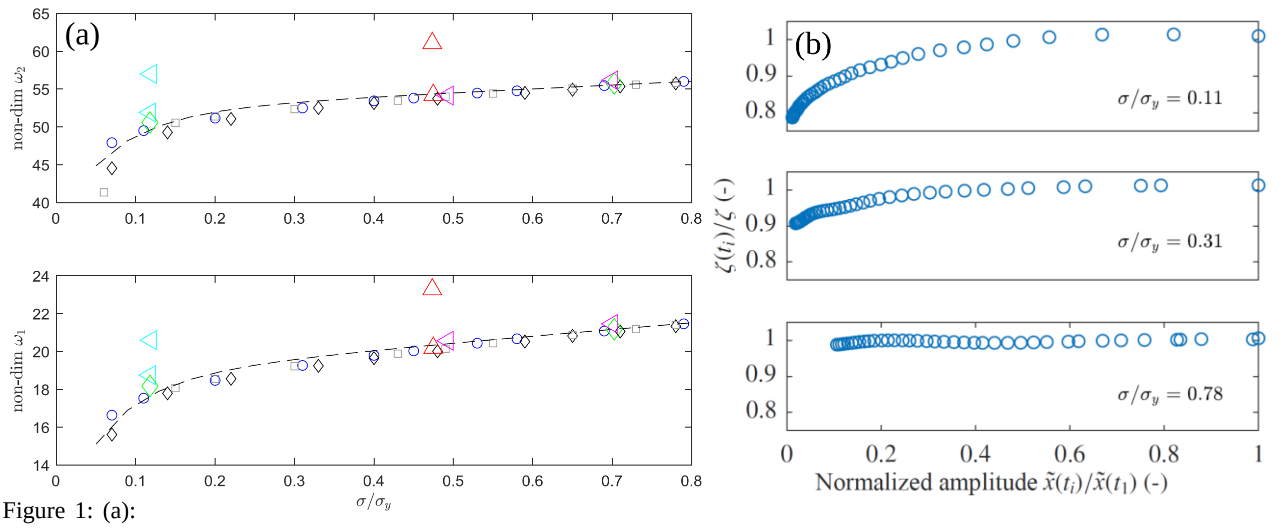

Figure 1: (a):
Transverse natural frequency as function of bolt tension: small markers: single bolt experimental data; everything has been taken apart between each color. Large markers: data from a two-bolt setup. Dashed line: theoretical tension-stiffness model adapted from [2]. (b) Time-dependent damping ratio as function of normalized acceleration amplitude.

Nonlinear effects and modal coupling between bolts

Investigations of vibration amplitude dependencies (thus nonlinearity) of the above mentioned bolt tightness indicators, damping ratios and frequency, have revealed to be of significance only under certain circumstances [6]. For practically relevant ranges of excitation level, the transverse natural frequency of a single bolt in a solid cylinder is effectively independent of vibration amplitude [6]. However, the linear damping ratio is not. Figure 1(b) shows the amplitude dependency of the damping ratio (of the first natural frequency) for three levels of tension. It drops for lower tension and smaller amplitude.

Another issue is coupling of vibrations between different planes. A bolt has a symmetric cross section, so there is a possible coupling between the two transverse directions, which appears to be driven by linearly acting imperfection [8]. Another coupling is the nonlinear coupling between transverse and longitudinal vibrations, which can occur in tensioned beams [9]. This nonlinear effect, in combination with imperfections, can allow for exciting transverse vibrations from a longitudinal impact [10].

New experimental results reveal that coupling between two bolts with almost identical tension and boundary stiffness appear to behave as a single coupled system, with co-and anti-phase modes [11]. However, this is only seen for cases where the tension is almost identical, for two bolts with different tension, it appears that interpreting the two bolts as separate entities with separate vibrational response is adequate. This may be the case due to an unknown nonlinear effect: A 1D-beam model of two beams coupled with springs will predict that the anti-phase mode has a higher frequency than the co-phase mode, as pulling in opposite directions will activate the coupling spring and increase boundary stiffness. Experiments show very similar behaviour. Figure 1(a) show also large color markers in pairs; these are measurements from a setup with two bolts and the frequencies are extracted from accelerometer measurements of one of the bolts. For cases with equal tension, there is a jump in frequency, both for first and second mode. However, for two bolts with even slightly different tension, the results are as for two single uncoupled bolts. To be able to fit a 1D-beam model to the measurements of all the cases, it is necessary to change the value of the coupling spring, leading to the question if this can be better explained as a nonlinear vibrational coupling between tension and bending. To investigate this we will introduce a nonlinear coupling spring and compare the results to the linear model.

Conclusions

The first steps in estimation of tension by vibrations have been taken. It is possible to measure natural frequencies and damping ratios in a single bolt and use these as bolt tension indicators. Nonlinearity has been investigated, and shows to be influential only under certain conditions. Tests with multiple bolts show many similarities with results of a single bolt, though under certain conditions coupling can occur, and that coupling can potentially best be modeled as nonlinear. This will be investigated further and updated results will be presented at the conference.

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