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Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Brøns, M., & Thomsen, J. J. (2019). Vibration-based estimation of bolt tension – coping with unknown boundaries. Abstract from Tribomechadynamics Conference 2019, Houston, Texas, United States.

Vibration-based estimation of bolt tension – coping with unknown boundaries

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In large engineering structures, such as pressurized pipelines and wind turbines, there are many critical bolted connections. Such structures are often under legal demands for ensuring the necessary bolt tension in the joint to avoid failure. Recent work investigates using vibrations for estimating tension in a bolt [1]. By exciting a bolt end transversely, with e.g. a simple hammer impact, and analyzing natural frequencies and damping ratios, an estimate of tension can be made. If an estimate is to be based on multiple transverse natural frequencies, insights are needed. This work looks into the effect of boundary stiffness on multiple natural frequencies when modelling the bolts' vibrations with a beam model.

At low tension, the squared natural frequency of the first bending mode increases strongly with tension. As the bolt is gradually tightened, the squared frequency starts changing more weakly and approximately linearly with tension [1]. Figure 1a shows this for experimental data obtained by hammer impacts on a single bolt in a structure. Relatively, the higher the bending mode, the less dependent the corresponding natural frequency is on tension. However, in absolute values the frequency change due to increased tension is much larger, as the frequencies are higher. Thus, if measurement errors are absolute and not relative, using higher modes for estimation is preferable.

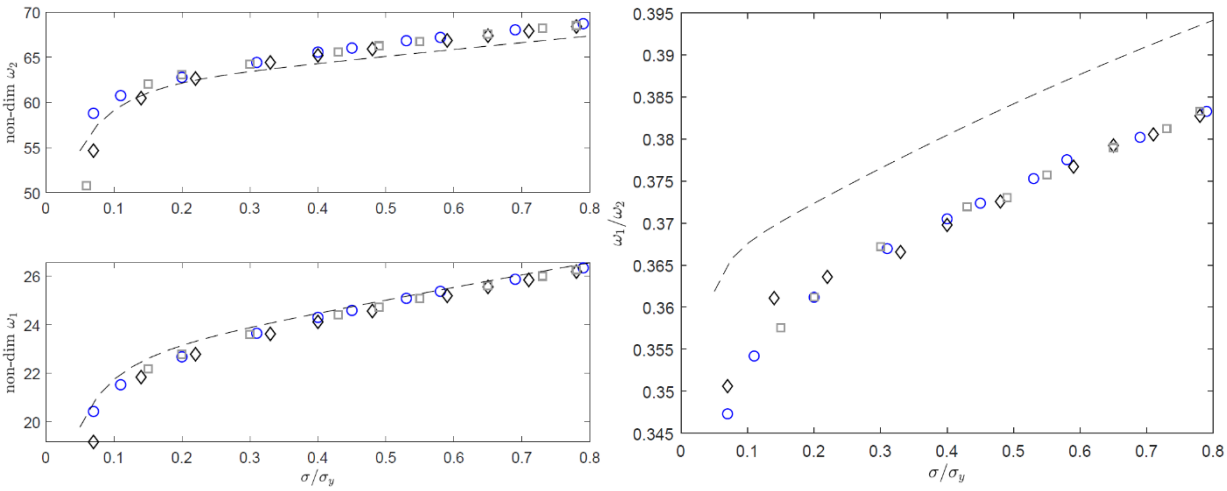

Figure 1: (a): Example of measured first and second natural frequency (nondimensional) as a function of tension. Three different test series indicated by ○, □, ◊. Dashed line: prediction of simple beam model. **(b):** Relationship between first and second natural frequency.

A tightened bolt can roughly be modelled as a uniform straight linear beam subjected to axial tension, and with a finite-valued transversal and rotational boundary stiffness that increases with increased axial tension. Figure 2 illustrates this interpretation. The approximating analytical function from [1] expressing axial boundary stiffness as function of bolt tension is used:

$$k_n = \frac{c_1 \tanh(c_2 p)}{1 + c_3 e^{-c_4 p}}, \tag{1}$$

where k_n is the axial stiffness, $c_{1\text{-}4}$ are positive constants determined by fitting to experimental data, and p is the nondimensional tension. The axial stiffness relates to translational ($K_{1\text{-}2}$) and rotational stiffness ($K_{3\text{-}4}$) by constants defined by geometrical properties, given in [1].

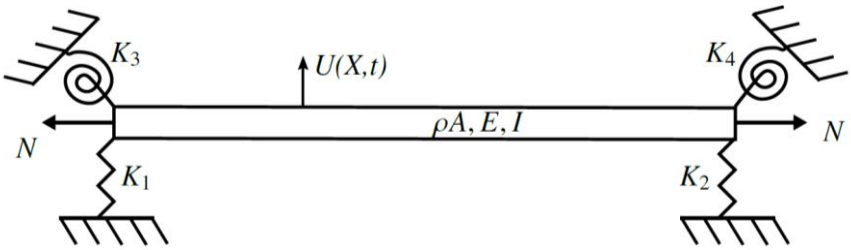

Figure 2: Interpretation of a tightened bolt: A beam in tension N with boundary springs $K_1, K_2, K_3,$ *and* $K4$.

However, this simple model does not work well for predicting transverse natural frequencies for more than a single bending mode: It neglects too much to be a sufficient multi-mode representation of a tightened bolt. In Figure 1b it can be seen that there is a discrepancy between model prediction (dashed line) and experimental data (○, □, ◊) for the ω_1/ ω_2-relationship.

By making a slight improvement to the inertia characteristics of the beam model, which includes a more detailed, though still simple, representation of a tightened bolt and its boundaries, it is possible to predict multiple natural frequencies accurately, with the same boundary model parameters. Figure 3 shows the results for the modified model. The same analytical function, expressing boundary stiffness as function of bolt tension, is used as before, but (1) has been fitted to the modified model changing the constants $c_{1\text{-}4}$. The results show significant improvement in the ω_1/ ω_2-relationship and now both first and second natural frequency can be used to estimate tension.

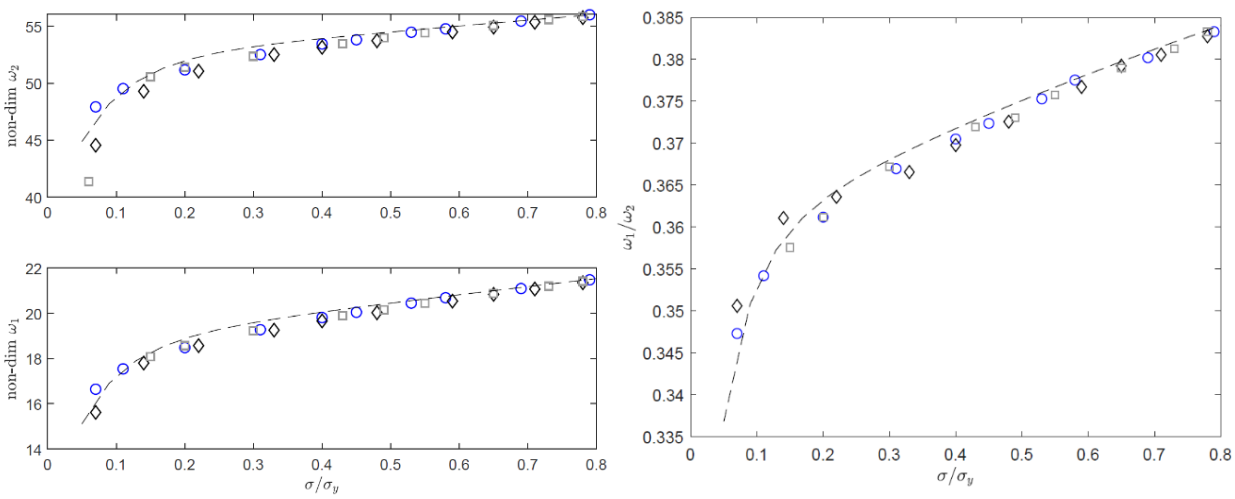

Figure 3: Example of measured first and second natural frequency (nondimensional) as a function of tension. Three different test series indicated by ○, □, ◊. Dashed line: prediction of *modified* beam model. **(b):** Relationship between first and second natural frequency.

Acknowledgment: This work is financially supported by the Danish Council for Independent Research, grant DFF-6111-00385.

References

[1] Sah, S. M., Thomsen, J. J., Brøns, M., Fidlin, A., & Tcherniak, D. (2018). Estimating bolt tightness using transverse natural frequencies. *Journal of Sound and Vibration*, 431, 137–149. https://doi.org/10.1016/j.jsv.2018.05.040