Determination of preload in bolts by ultrasound without referencing in unloaded state

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Abstract. The detection and monitoring of preload in bolting is an omnipresent need in structural mechanics without sufficient solution. A detailed study about the preload in bolts and its detection with a combination of different types of ultrasonic waves is presented. The accuracy of preload measurement based on relative time-of-flight variations between different wave types was investigated. For this purpose a system was built to adjust defined stress states in bolts and correlate them with ultrasonic time-of-flight measurements. In a first step the influence of stress on every single type of wave and the repeatability of time-of-flight measurement in the bolt were determined. This led to a good estimate of the measurement error and defines the minimum and the step size of preload detection. Additionally the bolt’s microstructure caused by the production process and the thread geometry are very important factors for the interaction of ultrasound with the bolt. Taking these boundary conditions into account, it is possible to define a material based acoustoelastic parameter which enables detection of stress levels in bolts of the same material and dimension. The necessary verification of this special acoustoelastic parameter is also possible with the preload-adjustment-system. The mentioned system provides full control over ultrasound generation, measurement and data handling in combination with precise mechanical measurement of the applied load. In the following investigations a comparison of parameters between different bolt diameters and lengths were performed to quantify dimensional effects and their contribution to the measurement error. Regarding the potential use in on- or offline monitoring systems a comprehensive database is crucial to investigate bolts of different materials and dimensions as well as easy-to-use GUI.

1. Introduction

The concept of preload is omnipresent in advanced bolting applications with safety relevance. However no general solution for preload adjustment and monitoring exists. The most widely used implicit methods to estimate the adjusted preload are torque measurements, rotation angle measurement or combinations of them. Common problems are inconstant factors like friction or pressure causing random deviations within the bolt tightening process. With these methods it is neither possible to adjust preloads reproducibly nor to check existing bolts on their conditions.

Thus ultrasound is very interesting for bolt tightening, because ultrasonic waves propagating trough a bolt are directly influenced by the preload. Such systems use the acoustoelastic effect in combination with the elongation under load. The Intellifast solution uses a piezoelectric transducer directly bonded on the bolt’s head [1] whereby the costs for these parts are relative high. Furthermore different online-bolt-tightening systems are
designed at Fraunhofer IZFP Saarbrücken using ultrasonic longitudinal waves to control the preload during bolting [2].

Under these circumstances the presented approach shall combine the precision of the online measurement with a second type of ultrasonic wave and material based knowledge to determine the preload of bolts without measurements of the initial length or time-of-flight.

2. Theoretical Background

The basic knowledge about nonlinear elasticity and its influence on the propagation of elastic waves in solids goes back to Murnaghan [3] and Huges/Kelly [4]. These physical principles allow the calculation of stress and deformation considering changes in ultrasonic velocity and consequently in the ultrasonic time-of-flight. Under consideration of the Young’s modulus \( E \), the density \( \rho \) and Poisson’s ratio \( \nu \) the ultrasonic velocity for longitudinal and transversal waves propagating in the same direction in an isotropic material can be written as:

\[
\begin{align*}
    c_{\text{long}} &= \frac{L}{t_{\text{long}}} = \sqrt{\frac{E(1-\nu)}{\rho(1-2\nu^2)}}, \\
    c_{\text{trans}} &= \frac{L}{t_{\text{trans}}} = \sqrt{\frac{E}{2\rho(1+\nu)}}.
\end{align*}
\]

(1)

(2)

Thus a quotient for the ultrasonic time-of-flight which is only dependent on the Poisson’s ratio can be written:

\[
Q = \frac{c_{\text{long}}}{c_{\text{trans}}} = \frac{t_{\text{trans}}}{t_{\text{long}}} = \sqrt{\frac{2(1-\nu)}{1-2\nu}}.
\]

(3)

A proportional dependency of the factor \( Q \) on uniaxial stress is given, regarding the proportional relation of acoustic velocities described through so called acoustoelastic constants [5]. They are described with the elastic constants of second and third order and depend on the direction of polarisation of the propagated wave in relation to the main direction of stress. [6]

Therefore, the factor \( Q \) is suggested to be suitable as indicator for a present uniaxial stress which can be directly deduced from the time-of-flight of a longitudinal and a transversal ultrasonic wave.

3. Materials and methods

3.1 Force adjustment and measurement

The bolts analysed in this work are preloaded on a custom-made device especially designed at IZFP as shown in Fig. 1 for the task of defined stress adjustment. Therefore the bolts are centred over a load cell and screwed into an adapter bridging the different thread diameters. The load cell (type 8524) is built by Burster Gmbh & co kg with a maximum load of 200kN with a precision better than 250N [7] and connected to the measurement PC with Burster USB multisensor interface [8].
The load is manually adjusted with a wrench to build up the preload between the dome covering the load cell and the bolt’s head. For the processing and storage of the generated force values a LabVIEW based program is used.

3.2 Ultrasonic measurement

To investigate the preload dependency of the ultrasonic velocity of different wave modes their time-of-flight has to be determined very precisely. The measurement system consists of two PC’s equipped with an integrated IZFP-made ultrasonic transceiver card working in pulsed mode. This device is well proved in industrial systems for stress evaluation for example in online-bolt-tightening systems [2] or residual-stress-analysis for railroad wheels [9] and provides preprocessed A-scans for the software with a resolution of 12.5 ns per pixel.

For the experiments two types of ultrasonic transducers are used, both longitudinal and transversal are declared with a frequency of 5 MHz and have a diameter of 10 mm.

The evaluation of the ultrasonic signals for time-of-flight measurement is realised with software developed at IZFP for online-bolt-tightening systems [2] which analyses the signals mathematically. Thus a sub-pixel precision of about 1 ns is reached for the time-of-flight between two echoes of the backwall.

3.3 Tested bolt samples

The bolts for this experiment are chosen from two strength classes, two lengths and two different manufacturers. Furthermore, head and counterside of the bolts are partly processed. A summary of all boundary conditions of the samples is listed in Tab. 1.
Tab. 1. Overview of bolt samples

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Dimension</th>
<th>Strength Classification</th>
<th>Head Processing</th>
<th>Counterside Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schrauben Jäger</td>
<td>M20x200</td>
<td>12.9</td>
<td>none</td>
<td>turned</td>
</tr>
<tr>
<td></td>
<td>M20x200</td>
<td>10.9</td>
<td>turned</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M20x150</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nedschroef</td>
<td>M20x200</td>
<td>HV 10.9</td>
<td>turned</td>
<td>turned</td>
</tr>
<tr>
<td></td>
<td>M20x150</td>
<td></td>
<td>none</td>
<td>none</td>
</tr>
</tbody>
</table>

All bolts tested of the class ‘HV 10.9’ fulfil DIN-EN 14399 standard, all other bolts fulfil DIN 931.

4. Results

4.1 Performed experiments and evaluations

In general all bolts are preloaded with a wrench in almost equidistant force steps with documentation of time-of-flight for longitudinal and transversal waves as well as the value of the force. In addition, the positioning of the ultrasonic transducers within the measurement is carried out manually.

On the one hand the reproducibility is tested with independent screwings on the same bolt on different days with slightly different environmental conditions and on the other hand the stress dependency of the ultrasonic velocities of longitudinal and transversal waves is compared within a random sample of one bolt type. Finally the quotient of the two ultrasonic velocities is compared between the different bolt types to understand the factors influencing this theoretically constant material property.

4.2 Evaluation

To assess the reproducibility of the measurements, a bolt of each length, 150 and 200 mm, is selected and loaded up to 110 kN in steps of about 10 kN several times. Fig. 2 shows the relative time-of-flight measurements with the highest variance for each length whereby the curves for a bolt length of 200 mm scatter more than for the shorter ones.
Fig. 2. Reproducibility of relative time-of-flight measurements performed repeatedly with one bolt of each length with complete unloading and disassembly between runs.

This result is in good agreement with preceding studies [5] and validates the estimation that one force cycle per sample is sufficient to characterise the potential of the method and to design further experiments.

For the random samples of bolts the quotient of equation (3) is plotted against the measured forces. Fig. 3 shows a representative average curve for every type of bolt mentioned in Tab. 1.

Fig. 3. Average curves for the quotient of the time-of-flight of transversal and longitudinal waves.

A significant difference of the time-of-flight quotient between samples can be observed as well as the fact that the slopes of all samples are comparable.
5. Conclusion

5.1 Discussion

Regarding the results of the experiments in Fig. 3, the coincidence of the slopes indicates that the acoustoelastic constants for the longitudinal and transversal waves seem to be mostly independent of the bolt type and strength classification in the tests, whereas the relation between ultrasonic time-of-flight values of the two wave-types differs a lot. A possible reason is given by equation (3) because of differences in the Poisson’s ratio due to production of the bolt’s head and the thread or due to properties of the alloy used for the wire.

Nevertheless it is possible to measure the preload in a bolt without unloading. Assuming that the factor Q is characteristic for a certain type of bolt material, geometry and processing, this factor could be determined for one unloaded bolt allowing the investigation of other mounted bolts of the same type concerning their magnitude of preload.

5.2 Outlook

The main task for further investigations should be an increased study with systematic variation of geometrical and material properties, working out rules for the mechanical values measured with ultrasound. This could lead to a reliable proposition of possible usability in on- or offline monitoring of bolts.

Thus it will be necessary to develop adapted ultrasonic transducers for the testing of bolts with frequencies and apertures optimized for the task. For instance the generation of a transversal wave should be realised with an electromagnetic transducer because there is no need for a coupling medium and this method is less sensitive for the surface inhomogeneities of the bolt’s head.

Another important and not yet investigated question is the long term development of the acoustoelastic constants in preloaded bolts. In static and dynamic tests the stability of the material properties calculated from time-of-flight measurements should be ensured under different environmental conditions.

References

