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Evaluation of the bi-wave method for ultrasound preload determination in the field with machine learning

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Summary:
Preload determination in bolts via ultrasound measurements is still a challenging task. Effects like scattering, interference and mode conversion produce signal distortion, which can cause invalid time-of-flight measurements and yield unreliable preload determination. There are different methods to detect invalid signals and eliminate them from the data analysis. However they have mostly been applied on controlled laboratory scale data sets. This paper evaluates the extension of these methods to more complex data collected on a wind turbine shaft.

Keywords: Ultrasound, Time-of-flight measurement, Preload determination in bolts, Machine Learning, Non-destructive evaluation 4.0

Introduction

Preload determination during the bolting process and the life cycle of bolted joints is an important topic to ensure defined and safe connection between different mechanical parts. Common methods like the torque or pressure measurements allow an indirect measurement of the preload during to the bolting process.

An alternative approach is to use ultrasound to evaluate the preload in bolts. Ultrasound measurements allow a direct determination of the preload, because the time-of-flight change directly correlates with the stresses in the bolts. Ultrasound offers two possible methods two measure the preload.

One-wave method

The one-wave method is well described and is already established for industrial applications. This method only utilizes the longitudinal wave mode to calculate the time-of-flight change compared to the unloaded state. The measured time-of-flight change allows calculating the preload directly via the acousto-elastic material constant, as described by Murnaghan, Huges and Kelly. [1][2]

The one-wave method requires a reference measurement of the time-of-flight in the unloaded state, which is its biggest limitation as it is not always available in the field, like for already build in bolts.

Bi-wave method

In contrast to the one-wave method, the bi-wave method enables the determination of the preload without referencing to the unloaded state by combining time-of-flight measurements for both longitudinal and transversal waves. The quotient of the two time-of-flight values provides the so-called Q_0 factor (see eq.1) which only depends on the Poisson’s ratio of the material. [3]

$$Q_0 = t_{0trans}/t_{0long}=sqrt((2*(1- v))/(1-2*v)) \quad (1)$$

$$Q = t_{trans}/t_{long} \quad (2)$$

The Q factor, see eq. 2, correlates linearly with the uniaxial stress and therefore enables the preload determination in bolts without a reference state. For using the bi-wave method in field applications, the unloaded Q factor can be determined on equivalent bolts and used for all bolts of the same material and geometry.

Problem

Due to the complex geometric structure of bolts the ultrasonic signals are highly influenced by interference and mode conversion. The high precision time-of-flight measurement, which is mandatory for preload determination, becomes a challenging task. The above-mentioned effects results in time-of-flight shifts, which limit

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the application of the bi-wave method to laboratory environments. [4]

Preload Measurements

In the current work, ultrasonic preload measurements were performed on a wind turbine shaft. In total 78 M42 bolts with a length of 670 mm were investigated. All bolts were measured with the two wave modes in the unloaded and in the loaded state. Additional monitoring measurements during the life cycle of the shaft were carried out.

During the initial tightening process, the time-of-flight change of the longitudinal waves is recorded to track the preload, see Figure 1. These preload curves can be the basis of an automatic labelling procedure for the longitudinal wave data.

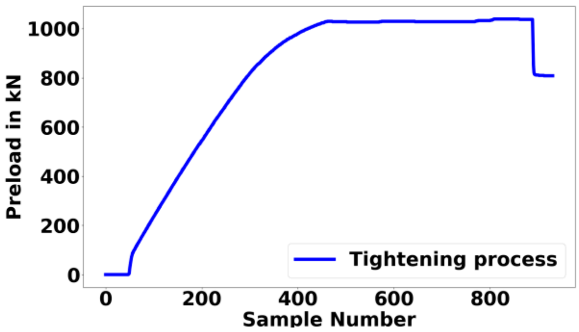

Figure 1: Preload curve during the tightening process of a bolt over the number of recorded A-Scans.

A comparison of the calculated preload value after finishing the tightening process between the one-wave and bi-wave method is displayed in Figure 2.

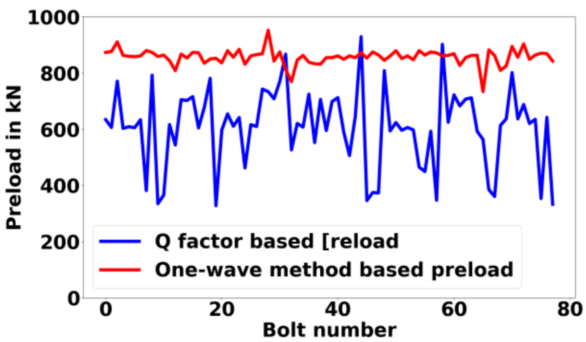

Figure 2: Calculated preload based on the one-wave method (red) compared to the bi-wave method (blue) without any signal validation.

The time-of-flight change calculation of the one-wave method is performed with the autocorrelation function of the first backwall signal to ensure valid and stable results. For the bi-wave method, the cross correlation function is used to determine the time-of-flight, because commonly for the bi-wave method the reference signal is not necessary.

The difference of the two preload curves is caused by different effects like material properties, slightly different bolting conditions, but also due to phase shifts in the time-of-flight measurement of both wave types.

In current work, the different influences are investigated. Especially the phase shifts occurring during the ultrasonic measurements will be addressed during the processing and analyzing of the signals. The aim is to build an artificial intelligence model capable of detecting phase shifts. With such a model the invalid signals could be eliminated and the failure in the calculation of the time-of-flight values can be avoided, by which the accuracy and reliability of the bi-wave method increases.

Moreover, an AI model would contribute significantly to bring the advantages of the bi-wave method closer to the application in field because a parametric model would ensure the validity of the ultrasonic signals and no advanced user knowledge would be necessary for an ultrasound-based preload detection.

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