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# Using COMSOL to Support a Cost-Effective, Non-Destructive Evaluation Approach for Predicting Bolt Failure in Highway Bridges

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**Abstract:** In this paper, the development of a quantitative nondestructive evaluation method, as an alternative to visual inspection, for inspecting pre-tensioned bolts in fracture critical bridges is presented. The method is based on frequency domain variables, which are affected by bolt size, length and pre-tensioning level. In order to understand the ultrasonic behavior of a wide variety of bolt geometries used in bridges, numerical models of nine different bolt geometries were developed in order to compare the ultrasonic behavior of bolts that were loose or tensioned. The numerical models included the acoustoelastic behavior of the tensioned bolts using hyperelastic Murnaghan material model, which represents the nonlinear relationship between stress and wave velocity. Additionally, two bolt geometries were experimentally tested using a longitudinal perturbation generated by a piezoelectric actuator, and propagating elastic waves were recorded using another piezoelectric sensor. The numerical and experimental results were compared.

**Keywords:** Pretensioned bolts, acoustoelasticity, nondestructive testing

## 1. Introduction

Bolted bridge connections are predominantly slip-critical. These connections rely on the friction developed between two or more plates that are bolted together to provide the necessary connection strength. Bridge connections tend to be slip-critical due to the inherent fatigue loading that bridges experience. Bolts in a non-slip-critical connection have a high failure rate when exposed to fatigue loading. Another advantage of this connection type is that upon failure (i.e. the plates slip), the load is then transferred to the bolts as a shear load and will not necessarily be catastrophic. As classical mechanics tells us, the force due to friction is the product of the force acting normal to the plane of slippage and the friction coefficient, an empirical material property. In order to overcome slippage, a sufficient amount of normal force must be present. In bridge connections, this force is developed by the tightening of the nut and bolt, which in turn increases the tensile force in the bolt. The Federal Highway Administration (FHWA) has developed minimum values for the tensile force present in slip-critical, bolted bridge connections. The current bridge bolt inspection practice is visual. However, visual inspection cannot identify the level of pretensioning which may be reduced due to environmental (e.g. corrosion) and mechanical (e.g. fatigue) factors. Despite the limitations of visual inspection, there is currently no commercially available nondestructive testing method to measure the level of pretensioning in slip-critical bolts.

There are several studies in the literature which use nonlinear ultrasonics to correlate the frequency shift with pre-tensioning level due to bolt elongation in the longitudinal direction (Heyman 1977) and nonlinear stress-velocity relationship based on the acoustoelastic theory (Johnson et al. 1986, Chaki et al. 2007, Hirao et al. 2001, Kim and Hong 2009, Yasui et al. 1999). In order to decouple changes in the arrival time due to the bolt elongation and the stress dependent velocity, initial bolt length should be known. Additional bolt geometry (i.e. diameter) also plays a significant part in how ultrasonic waves propagate through a bolt.

Bridge bolts typically come in much different sizes than do typical mechanical assembly threaded fasteners. Additionally, bridge bolts themselves come in a variety of diameter and lengths. Unfortunately, the majority of studies have not tested their methods on more than two bolt geometries (e.g., Chaki et al. 2007, Hirao et al. 2001, Yasui et al. 1999). Understanding the effects of bolt geometry is important, and any acceptable method for determining prestress must accommodate these various geometries. Further complicating matters, the test results should be independent from surface condition and paint thickness.

In this study, COMSOL software is used to model different bolt diameters and lengths in order to understand how the frequency spectrum of a given bolt diameter and length changes under different pretensioning values. The material model is selected as hyperelastic Murnaghan in order to consider the effect of pre-tensioning in the frequency response history.

The loading function is defined in the frequency domain and introduced into the program using an interpolation function. Frequency domain loading causes a perturbation at the head of the bolt, and the observation point is the bottom of the bolt where the receiving sensor is placed for the ultrasonic measurement. Numerical results are compared with the experimental results for validation.

## 2. Theory

Longitudinal waves in circular bolt geometry create displacement components in the axial and radial directions. The presence of pretensioning causes both the elongation of the bolt that changes the resonant frequencies and the change in wave velocity explained by the acoustoelastic theory. The acoustoelasticity is based on the finite deformation theory (Murnaghan, 1951) resulting in the nonlinear relationship between stress and wave velocity. The system kinematics are defined by the Green strain, and the stresses are represented by the second Piola-Kirchhoff stress that is solved using Lagrangian formulation (Norris 2008)

$$\rho_o \frac{\partial^2 \boldsymbol{U}}{\partial t^2} = \boldsymbol{\nabla}_a . \boldsymbol{P}$$

where $\rho_o$ is density, $\boldsymbol{U}$ is the Lagrangian displacement as a function the material coordinate *a* and time *t*, $\boldsymbol{P}$ is the first Piola-Kirchhoff stress tensor.

The geometric nonlinearity of the structure due to the presence of stress causes a relationship between stress level and wave velocity. For the wave propagation in longitudinal direction, the wave velocity *V* and stress *T* relationship is (Hughes and Kelly 1951)

$$\rho V^2 = \lambda + 2\mu - \frac{T}{3K}[2l + \lambda + \frac{\lambda + \mu}{\mu}(4m + 4\lambda + 10\mu)]$$

where ρ is density, λ and μ are Lame' constants, *l* and *m* are third order elasticity constants.

The displacement solution of longitudinal waves in bar-like structures considering the lateral inertia effect depends on the bar length (Graff 1975 p.123). When the bolt geometry studied in this research is extended due to pretensioning, the response history and its frequency spectrum are modified. Therefore, the effects of bolt elongation and acoustoelastic effect in longitudinal direction are coupled during the longitudinal ultrasonic wave measurement.

## 3. Use of COMSOL Multiphysics

The purpose of utilizing the COMSOL software is to understand the following variables: (a) the effect of plate presence on the frequency response of the bolt, (b) the change in the frequency response due to pretensioning for a given diameter and length bolt, and (c) the effect of bolt length and diameter to the frequency response variation due to pretensioning.

Three different diameter bolts with three different lengths were modeled for three loading cases, totaling twenty-seven computer runs in the testing matrix: diameters of 3/4", 7/8" and 1" in lengths of 2 1/2", 3 1/2" and 6" as shown in Table 1. All bolts were A325, Type 1, uncoated and coarse threaded. The diameters were chosen because they were found to be the three most common diameters used in steel bridges (FHWA 1991). A wide range of bolt lengths was used in order to maximize the observable effect that the length had on the ultrasonic wave propagation. This matrix allowed the comparison of different lengths with consistent diameter, as well as to compare the results of different diameters with consistent lengths. Additionally, the bolts were modeled with free and with plates attached fully at their peripheries.

**Table 1** – Bolt Geometry Matrix

| | | Length (in.) | | |
|---|---|---|---|---|
| | | 2 1/2 | 3 1/2 | 6 |
| Diameter (in.) | 3/4 | 3/4 x 2 1/2 | 3/4 x 3 1/2 | 3/4 x 6 |
| | 7/8 | 7/8 x 2 1/2 | 7/8 x 3 1/2 | 7/8 x 6 |
| | 1 | 1 x 2 1/2 | 1 x 3 1/2 | 1 x 6 |

Figure 1a shows the full scale bolt geometry. Suitable element size *l* suggested for finite element calculations of propagating elastic waves for a stable solution without any numerical pollution (Hill et al. 2004) is

$$l = \frac{\lambda_{min}}{20}$$

where $\lambda_{min}$ is the minimum wavelength involved. In order to develop an accurate frequency response behavior of bolts in the range of 50 kHz-150 kHz, the minimum mesh size needed is 2 mm. The model is simplified as a quarter model with two symmetry planes as shown in Figure 1b, which reduces the computational time. A 60-kHz sine wave with sine modulated shape is applied to the center of the bolt head. In COMSOL, the frequency domain excitation signal is applied to the loading point using an interpolation function. Figure 1c shows the quarter bolt model with the bonded plates. It is assumed that when the bolts are tensioned, there is perfect acoustic attachment between the bolt and the plate. For model (b), the boundary condition of the bottom surface of the bolt head is assumed to be fixed. For model (c), the boundary condition of the periphery of the attached plate is assumed to be fixed. The comparison of model (b) and model (c) shows the influence of plate presence (i.e. suppressing the axial deformation of the bolt under longitudinal perturbation), which has not been considered in previously published papers.

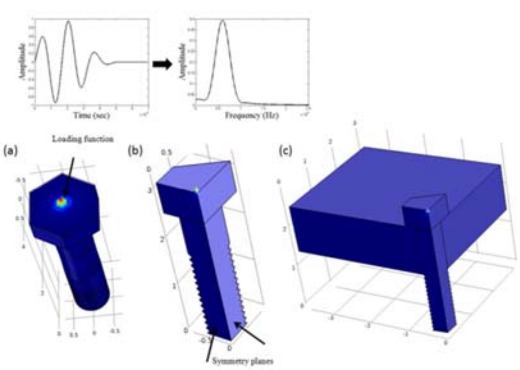


**Figure 1**. The model geometry, (a) full scale indicating the loading function, (b) quarter model with two symmetry planes, (c) quarter bolt model including the presence of plates

The material properties of the structural steel provided in the program are used, and the loss factor is defined as 2%. The material model is selected to be hyperelastic Murnaghan in order to consider the effect of tensioning in wave velocity or frequency response. Finally, the third order elasticity constants for the structural steel available in the COMSOL program are used.

The solutions include two steps: (1) stationary for introducing pretensioning, (2) frequency for frequency domain analysis under the applied frequency load as shown in Figure 1**.** The frequency range is set at 50 kHz – 150 kHz. The frequency step size analysis showed that 500 Hz step size provides an accurate frequency response of the bolt as shown in Figure 2.

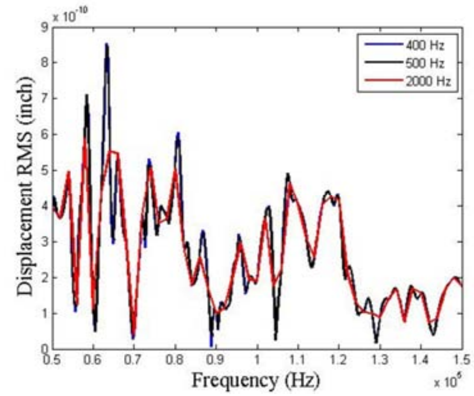


**Figure 2.** The comparison of the frequency response of 3/4**"** diameter, 2½**"** length bolt for three frequency step sizes

## 4. Results

### 4.1. The effect of plate presence on the bolt's frequency response

When the bolt is tensioned, the presence of the plates surrounding the bolt causes damping of radial deformation during the longitudinal perturbation, which results in the modified response function as compared to the "bolt only" model. The comparison of the models shown in Figure 1a and b under the same excitation source is shown in Figure 3. The displacement amplitudes decay significantly due to the restriction of the radial deformation by the plates, and the frequencies are modified as the boundary conditions of the bolt are different than the bolt only model. The effect of the plate presence on the bolt's frequency response in the range of 50 kHz to 150 kHz shows that the plates cannot be neglected in numerical models and experimental simulations. Figure 3 shows results for only one diameter and length bolt; however, the same results are obtained for other diameter-bolt combinations.

The modeling of higher frequencies requires very fine meshing, which causes long computation times. Therefore, the maximum frequency set in this study is 150 kHz.

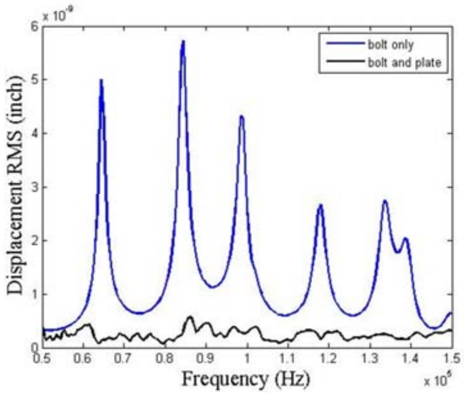


**Figure 3**. The frequency response behaviors of the bolt and the bolt/plate models for a 3/4" diameter, 3½" long bolt

### 4.2. The change in the frequency response due to pretensioning for a given diameter and length bolt

The analyses are performed only on bolts under no load and minimum pretensioning value and on bolts with plates under a pretensioning load. Figure 4 shows the frequency histories of a bolt with a 7/8" diameter and 3 1/2" length under no load and the minimum FHWA required pretensioning level. There is an approximate 2 kHz shift in the frequency harmonics of the bolt due to a 41 kip pretensioning.

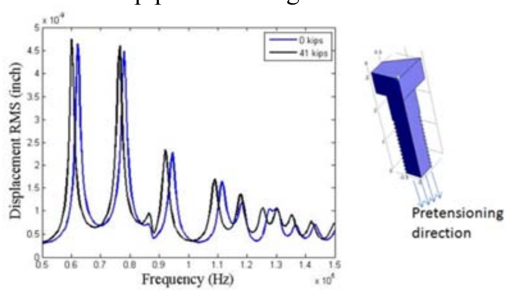


**Figure 4**. The frequency shift of the bolt only due to pretensioning for 7/8" diameter, 3½" long bolt

However, when the plates are considered in the model, the frequency response solution becomes quite complicated. Figure 5 compares the free bolt with no load (blue) and the bolt with a plate under pretensioning (black). There is no consistent frequency shift in this case as compared to Figure 4. The other bolt length-diameter combinations have been analyzed, and the similar result is observed.

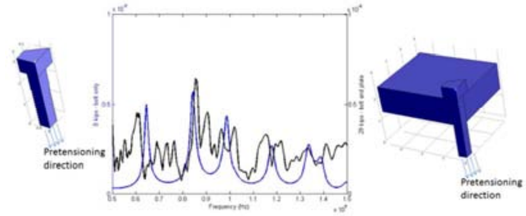


**Figure 5**. The comparison of displacement RMS at the bottom of the bolt due to no load (blue) and 29 kip pretensioning (black) for a 3/4" diameter, 3½" long bolt

### 4.3. The effect of bolt length and diameter to the frequency response

In order to study the variation in frequency response according to the change in bolt sizes, three different diameter bolts with three different lengths were modeled for different loading cases, as mentioned earlier. Figure 6 shows the frequency response variation of a bolt with a 3/4" diameter due to the change in bolt length under no load. The displacement RMS reduces accompanied with a frequency shift for higher bolt lengths.

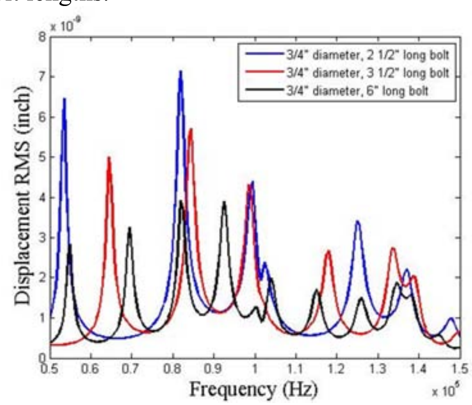


**Figure 6.** The frequency response variation of a 3/4" diameter bolt under no load and at three different lengths: 2½" long bolt (blue), 3½" long bolt (red), 6" long bolt (black)

The effect of changing bolt diameter on the frequency response is shown in Figure 7. This figure shows a frequency shift for smaller diameter bolts compared with a bigger diameter bolt having the same length, which agrees with the theory (more slender geometry with increasing the length for a given diameter).

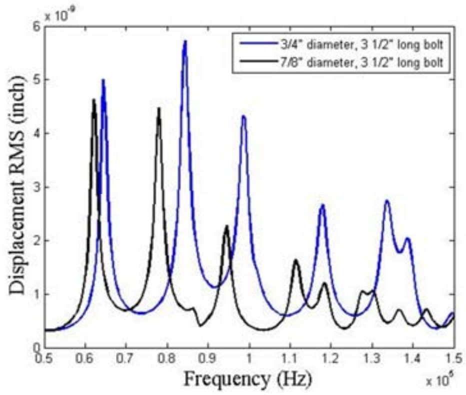


**Figure 7.** The frequency response variation due to change in bolt diameter under no load for 3 ½" long bolts with 3/4" diameter (blue), and 7/8" diameter (black)

## 5. Experimental Validation

### 5.1. Experimental Setup

In order to generate data for the loose, snug-tight and fully tightened cases, a simulated bridge connection was constructed in a laboratory setting (Figure 8 and Figure 9). A channel shape was drilled with three holes (3/4", 7/8" and 1" diameters) in order to simulate one of the connected members. The other members were simulated by using either 1/2" or 1" thick steel plates (or a combination of both), measuring about 3" x 3". These plates were also drilled individually with the three different diameters. A bolt was inserted through the various holes with a single washer on either end, and a nut was lightly threaded on the threaded end, simulating a loose case. The bolt was then tightened to snug-tight and fully tight conditions using an adjustable wrench. FHWA's *High-Strength Bolts for Bridges Manual, Table 11.5B – Nut Rotation From Snug Tight* was used to determine how many turns from snug-tight were required to obtain the correct bolt tension. In addition, the bolts were fitted with strain gauges in order to verify and quantify the presence of tension.

The bolt end had a curved surface; therefore, a miniature sensor was selected for this end as the excitation source (pico sensor manufactured by Mistras Group, Inc). The excitation signal was the same as the time-force function shown in Figure 1 (60 kHz 3-cycle sine wave with sine shape) and generated by a function generator with 5 Hz repetitive rate. A R6 sensor, which has 60 kHz resonant frequency, was placed on the head of the bolt as the receiving sensor. The actuating-receiving mode was continuously recorded using an eight channel data acquisition system during the straining test. The data acquisition system was synchronized with the function generator in order to identify the arrival time of the propagating waves from the excitation location to the received point. The sampling rate was set at 3 MHz.

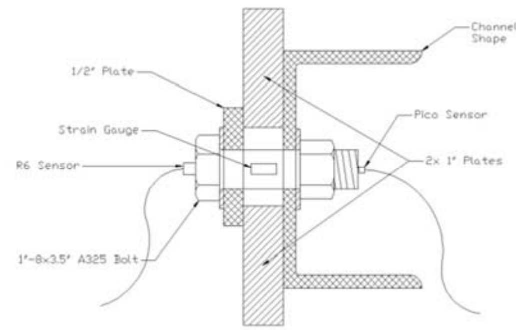


**Figure 8.** The drawing of the bridge connection simulated at the laboratory

**Figure 9.** The photographs of the laboratory testing

### 5.2. Experimental Results

Figure 10 compares the frequency spectrums of the 7/8" diameter and 3 1/2" long bolt tested under three cases: (1) bolt only, no pretensioning, (2) bolt attached to the plates, snug-tight condition, and (3) bolt attached to the plates, fully tight condition. The comparison of cases (1) and (2) shows that there is a slight modification in the frequency spectrum and some amplitude loss. However, the comparison of cases (2) and (3), in agreement with the COMSOL results, indicates that the tensioned bolt couples fully with the plates and causes the presence of the plates to be a part of the dynamic behavior of the bolt. There is also leakage of wave intensity towards the plates due to pretensioning, which leads to an energy loss of the propagating longitudinal waves from the actuating point (the top of the bolt head) to the received point (the bottom of the bolt).

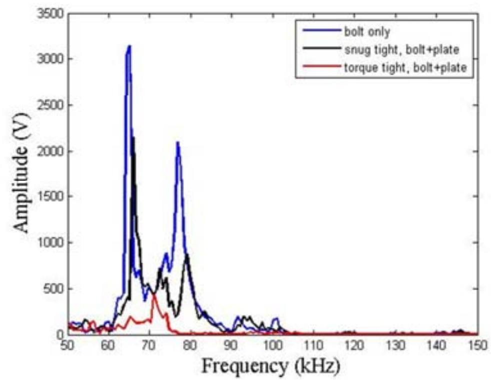


**Figure 10**. The frequency spectrums of the bolt only and the bolt/plate with snug tight and torque tight cases for 7/8" diameter, 3 ½" long bolt

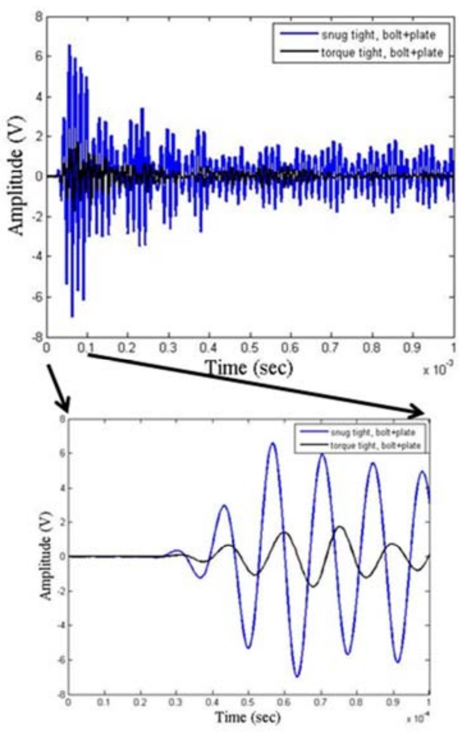


**Figure 11.** The waveform signatures at the snug-tight condition (blue) and the fully tensioned condition (black), (a) complete waveform, (b) detailed section of the first arrival waves

While there is no evident frequency shift due to pretensioning, if the complete waveform (Figure 11a) is analyzed, a detailed view of the transient waveform in the time domain indicates a delayed arrival time due to the bolt elongation and the acoustoelasticity as shown in Figure 11b. This experimental finding was observed in two geometries. However, in any case, if only longitudinal waves are introduced as the perturbation, the use of arrival time shift due to pretensioning requires an accurate knowledge of the initial bolt length to estimate the pretensioning level. Chaki et al. (2007) developed a bi-wave method (introducing longitudinal and transverse waves) to find the pretensioning level without a systematic calibration. However, the approach was demonstrated on a single bolt, without considering the connected plates.

## 6. Comparison of Experimental Results with COMSOL

Figure 12 compares the numerical and experimental results of the bolt only case for 7/8" diameter, 3 1/2" long bolt. The COMSOL result is displacement RMS (inch as the unit) at the opposite side of the perturbation while the experimental result is the electrical output (volt as the unit) of the piezoelectric sensor (R6 shown Figure 8) due to the surface motion. Two peak frequencies of two methods are close while higher order harmonics disappear in the experimental result, which is due to the resonant behavior of the piezoelectric sensor used in this study. Piezoelectric sensor model could be added to the COMSOL for multiphysics analysis for more accurate comparison.

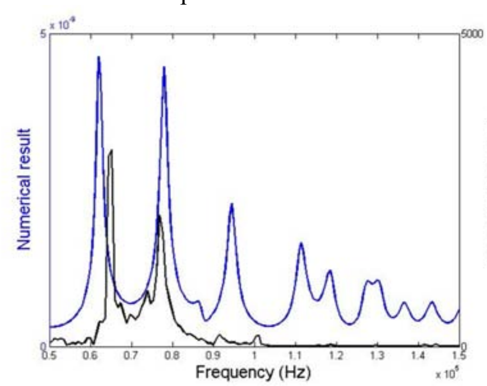


**Figure 12**. The comparison of numerical and experimental results of the bolt only for 7/8" diameter, 3 ½" long bolt

Figure 13 compares two methods for the pretensioned case. The COMSOL result is for the case of bolt/plate and minimum pretension level required by FHWA. The complexity of the test geometry shown in Figure 8 causes higher discrepancy in the frequency harmonics between the simplified numerical model and the experimental result. However, both methods indicate complex frequency profiles when the bolt is fully tensioned.

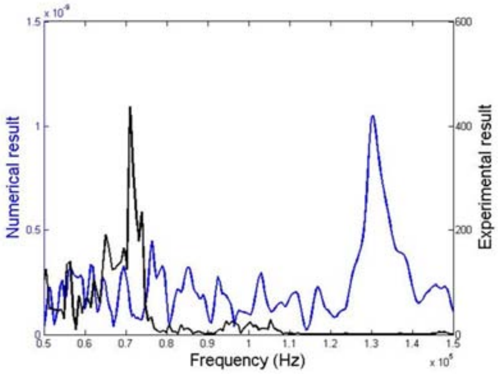


**Figure 13**. The comparison of numerical and experimental results of bolt/plate with torque tight (fully tensioned) for 7/8" diameter, 3 ½" long bolt

## 7. Conclusions

The COMSOL enabled an extensive parametric study to understand the effects of bolt diameter, length and pretensioning levels on the frequency response behavior of a given bolt. The numerical and experimental results show that the leakage of propagating longitudinal waves from the bolt geometry and the surrounding medium together with the radial deformation restriction during pretensioning modify the signature of the longitudinal waves in the range of 50 kHz – 150 kHz. It is concluded that the energy of the propagating waves in the longitudinal direction is proportional to the level of the pretensioning. The proportionality requires a reference energy level that is deducted from the laboratory testing. Non-contact focused ultrasonic sensors (e.g. EMAT) can be used to prevent the influence of the coupling condition on the ultrasonic measurement.

The loss of frequency harmonics of bolts under pretensioning does not require any reference point. However, such an observation is qualitative, and does not provide any quantitative information about the pretensioning level.

The time domain waveform obtained from the testing of bolt geometries shows an arrival time shift. The other bolt geometries will be tested to further verify this result. The numerical solution in the time domain is computationally expensive; therefore, a simplified solution is needed to confirm the experimental findings.

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