

Potentials and Limitations of Ultrasonic Clamp load Testing

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ABSTRACT

Ultrasonic clamp load testing is known as a sophisticated method for an in-situ determination of the load of a bolt in a joint. However certain limitations have to be respected. An overview about the method is given and the limits are presented. Special attention is paid to real time clamp load measurement of joints as well as the determination of the residual clamp load of yield tightened joints.

INTRODUCTION

The clamp load is the most important characteristics of a bolted joint. A loss of clamp load may lead to squeak and rattle or even worse to a failure of the joint with significant impacts on the safety of a vehicle. Thus the measurement of clamp loads in bolted joints is a critical issue for safety joints. The use of ultrasonic signals for this purpose is well known method. As a major benefit over the use of e.g. load cells and strain gages it allows to determine the clamp load without any impact on the joint stiffness. Due to that the method is classified as a nondestructive method.

However opposite to the use of load cells the method is an indirect method which is not only influenced by the stress in the bolt but also by temperature and plastic elongation leading to some limitations which have to be observed.

On the other hand improvements in the electronic devices over the last couple of years have opened new opportunities and fields where the method can be used.

It should be noted here for accuracy, that the term "clamp load" in this study refers to the load in the bolt. Depending on the joint configuration the actual load in the interface e.g. acting on a gasket might be significantly different especially under dynamic loads.

BASICS OF THE ULTRASONIC METHOD

The principle of the ultrasonic clamp load testing is quite simple. A sensor or transducer is put on one of the bolts ends preferably the bolts head. Its purpose is to convert an electronic signal into a mechanical vibration and vice

versa. The generated wave travels through the bolt, is reflected by the bolt's end and once again converted back into an electronic signal. The measuring device attached to the transducer measures the time between the transmission of the signal and the receipt of the echo. This is also referred to as the "Time Delay".

Now as the joint is tightened the bolt is elongated. This leads to an increase in the time delay. The stress induced in the bolt has an additional impact on the wavespeed also known as elastoacoustic effect. This causes a total time delay for an elongated bolt which is around 3 times higher than to be expected due to the elongation only.

It is understood, that only the difference in the time delays of the loaded bolt versus the unloaded bolt is of interest. In the following the term time delay is always used in this sense.

WAVE TYPES

Generally speaking two different wave types are known when working with ultrasonics for the clamp load measurement (Figure 1).

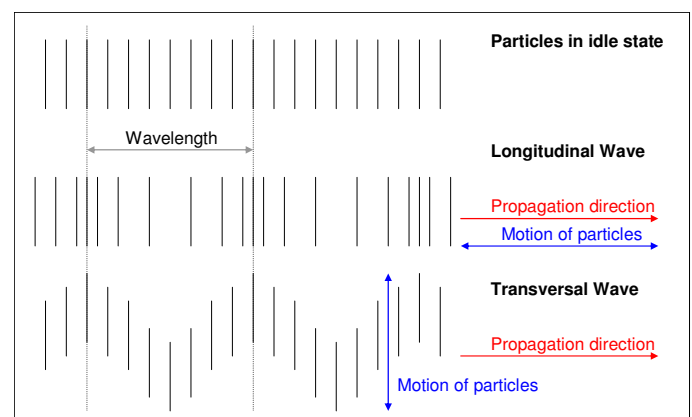


Figure 1: Ultrasonic Wave Types

For longitudinal waves the particles in the bolt swing in the same direction as the bolt's axis. For transversal waves the particles swing perpendicular to this axis. The speed of both waves is significantly different. For

standard steels the typical wavespeed is 5,900 m/s while the speed of the transversal waves is 3,200 m/s, so the speed ratio is around 1.8.

Most ultrasonic devices in the market use the longitudinal waves for the determination of clamp loads. The use of transversal waves requires special shear wave sensors as well as measuring equipment that is able to handle the two independent echoes.

However the transversal waves can act as an additional source of information to eliminate an unknown parameter such as the plastic elongation for bolts tightened to yield. This will be demonstrated later.

TRANSDUCERS AND COUPLING METHOD

Different approaches are known to attach the sensors to the bolt. They all have to achieve a reliable connection between the transducer and the bolt in order to transmit the wave into the bolt and vice versa as best as possible with a minimum loss of energy. This needs to be done having a constant and reliable timing behavior.

Looking into the details of the measurement chain shown in Figure 2 explains the problem.

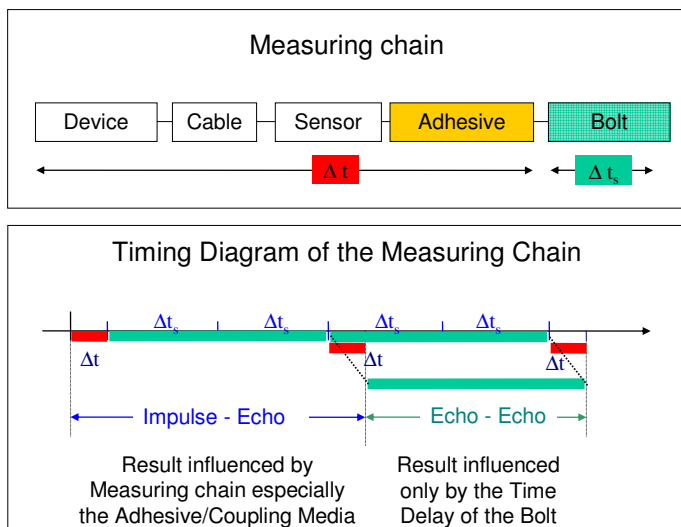


Figure 2: Timing Diagram of the Measuring Chain

The timing diagram for the common Impulse-Echo method includes the time delay caused by the measuring chain itself – excluding the bolt. While sensor, cable and device can be considered to have a stable time delay, the adhesive – or coupling media for some type of sensors – has a governing impact on the result. This applies especially for reusable electromagnetic transducers that are only loosely coupled to the bolt and where fluids like glycerin are commonly used as a coupling media. This type of attachment often leads to a varying gap thickness depending on the force which presses the sensor on the bolts head. The resulting impact on the time delay can cause significant scatter in the clamp load readings. For static measurements where the time for taking the measurement is

insignificant this might not be a problem as an average measurement may be taken to level out the problem.

For sake of completeness it should be noted, that the problem can be avoided by using the Echo-Echo method as depicted in Figure 2. However this method requires a good quality of the second echo signal which depends on the fastener configuration and thus can only be used in a somewhat limited number of applications.

The use of liquid coupling media is also impossible while using shear sensors as they do not transmit shear waves at all.

For real time measurements one also has to ensure, that this part of the measurement chain remains stable throughout the measurement. This is usually achieved by gluing sensors such as piezo sensors on the bolt.

Figure 3 shows the combined transversal/longitudinal sensor used in the present study for bolts tightened into the yield.

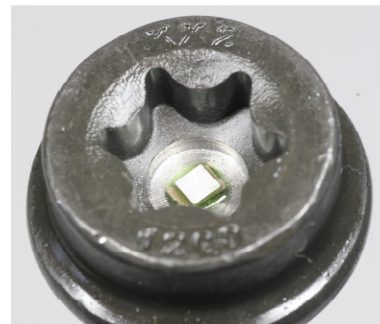


Figure 3: Piezo-Sensor used in the present Study.

The sensor in total consists of two piezo sensors that are stacked upon each other using an appropriate glue. Both sensors are plated with an electrically conductive material on both sides. This configuration allows to contact both sensors with only one connector, using the bolt itself as the electrical ground. The pulse transmitted by the measuring device stimulates both sensors concurrently. At the same time the receiver is setup using two independent logical measuring channels each of them configured to listen on one of the two echoes – one for the longitudinal, the other one for the transversal echo. Due to the speed ratio of 1.8 for standard steels the transversal echo is received shortly before the second longitudinal echo arrives at the sensor. This allows to set the time frames used for the identification of the echoes in the measuring device properly. For different materials like Aluminium or Titanium where the ratio is close to 2.0, an interference of the second longitudinal echo with the first transversal echo is observed. This makes it impossible to identify both echoes using this method. In these cases two individual physical sensors as well as independent excitations in time would be necessary to avoid the interfering echoes.

REAL TIME MEASUREMENT

Progress on electronic chips over the last decade has made devices available that integrate ultrasonic channels into transient recorders. Sampling rates up to 2 kHz and above can be achieved. These rates allow to record the tightening process in real time as well as monitoring e.g. process forces in-situ.

Figure 4 shows a process running at a speed that is comparable to live engine requirements. For this figure the bolt load in a hydraulic fatigue tester has been recorded using an ultrasonic transducer and the intrinsic load cell concurrently.

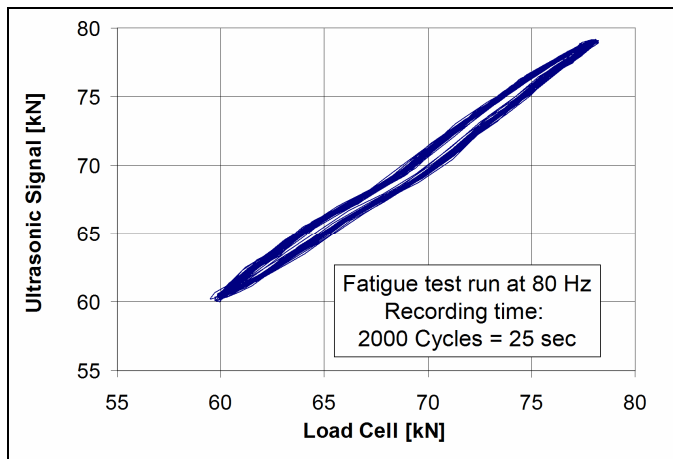


Figure 4: Comparison of Ultrasonic Bolt Load vs. Load Cell in a Fatigue Tester at 80 Hz.

The fatigue tester has been setup for an average load of 69 kN and an amplitude of +/-9 kN at a frequency of 80 Hz. The sampling rate of the ultrasonic transient recorder has been set to 2000 Hz. In Figure 4 the ultrasonic load is plotted versus the load taken from the fatigue testers load cell. The data shown have been recorded for 2000 cycles.

Besides a small shift in the phase between both signals that has been corrected for Figure 4, the data show a quite good relation. The ideal curve would be a single, straight line having a slope of exactly 1. The actual data exhibit the usual statistical scatter leading to a thick line. The oval shape of the curve is still caused by a small phase shift between both signals. However this phase shift is below 1/2000 sec. For the recording time of 2000 cycles no signal drop and no malformed reading of the ultrasonic signal has been observed.

Looking at the actual numbers an increase of 1.5 kN during the starting phase of the test had been observed for the ultrasonic load. This is attributed to a temperature change in the specimen.

Even if it does not really make sense to record the load of a bolt in a fatigue tester, this experiment was used to prove the general ability to do real time measurement of the clamp load of engine bolts in a running engine. While this would be a quite simple task for cylinder head bolts, it would be an interesting but challenging task to measure a con rod bolt in a running engine. However significant environmental obstacles such as cabling, the influence of aggressive oil on the sensor still have to be overcome. Also the temperature compensation remains an open issue as one even cannot assume that the temperature distribution over the bolt is constant which makes it even impossible to use temperature probes.

YIELD TIGHTENING AND RESIDUAL LOADS

The ability to record ultrasonic time delays in real time during a tightening test allows to approach another area of interest: the determination of the residual load of bolts that have been tightened into the yield. This is the case for most critical engine bolt such as cylinder head bolts, con rod bolts e.g.

PROBLEM

A bolt that is tightened into the yield has per se a defined clamp load which is purely determined by the strength of the bolt. However this remains true only during the tightening. As soon as the tightening tool stops, the torsional stress in the joint relieves resulting in a residual stress slightly below yield. During the next minutes the joint settles leading to a further release of the stress in the bolt. The bolt is in the elastic region again.

For the ultrasonic testing the plastic elongation of the bolt becomes a problem. The method can not differentiate between a purely elastic and a plastic deformation.

Two solutions exist to solve this problem. If longitudinal waves are used only, there is no way around a disassembly of the bolt.

This method is schematically shown in Figure 5. A bolt is tightened into the yield (Point A). Neglecting the effect of the relieve of torsional stresses and the settling process it may now happen that the bolt is further stressed to point B by external forces or different thermal expansion of the bolt and the jointed components. Even if the plastic deformation at point A might have been determined e.g. in a tightening test before, the plastic deformation at point B is unknown.

Now setting is assumed. Additionally the joint is cooled down to room temperature to enable an ultrasonic clamp load testing. Both effects lead to decrease of the bolt load to point C along the elastic line.

The clamp load can now be determined by untightening the bolt and measuring the difference in the ultrasonic time delay between point C and the completely unloaded bolt.

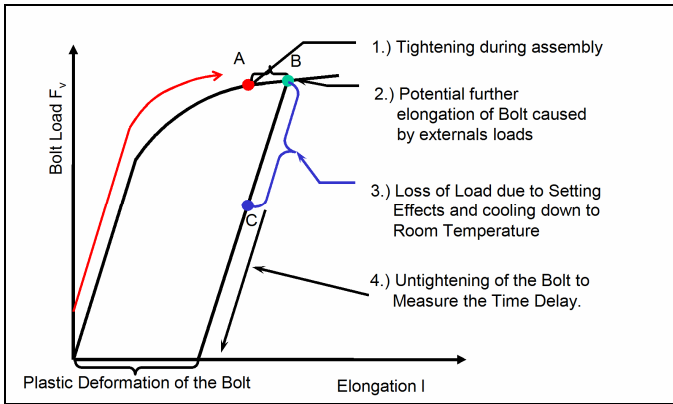


Figure 5: Determination of the Residual Clamp Load of a yielded Bolt

However it should be noted here, that the diagram has been simplified to focus on the principle problem. The stiffness of the joint – which is not shown in Figure 5 – may have a significant influence on the load in the bolt ([2], [4]).

MEASUREMENT OF RESIDUAL LOADS USING TRANSVERSAL WAVES

The method just described has the obvious drawback of destroying the joint. An alternative method is to use both type of waves – longitudinal and transversal waves concurrently.

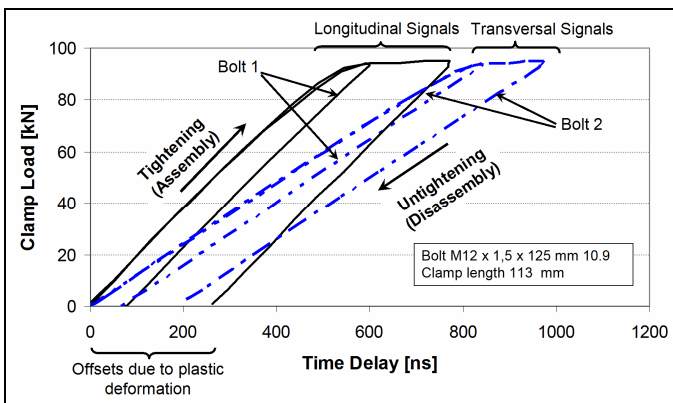


Figure 6: Behavior of Longitudinal and Transversal waves for yield tightening. (Bolt M12x1.5, 10.9, Clamp Length 113mm).

Figure 6 shows the time delay of both waves recorded for two bolts M12 tightened into the yield to two different levels of plastic deformation. The clamp load was recorded using a load cell in a test rig like shown in Figure 7. Figure 6 shows the complete tightening and untightening curves. It is demonstrated, that the transversal wave travels slower through the bolt than the longitudinal waves. The unloading path for each of the waves is somewhat parallel to the loading path. The remaining offset in the time delay after the unloading is caused by the plastic deformation of the bolt. It clearly shows that the influence of the plastic deformation on the longitudinal waves is higher than on the transversal

waves – the offset is around 250 ns versus 190 ns for the longitudinal waves for Bolt 2. This effect now allows a compensation of the plastic deformation leading to a method to determine the residual clamp load of bolts tightened into yield *without* the necessity to disassemble the joint. The principle idea is also found in [1].



Figure 7: Test-rig used in the present study

CALIBRATION

The calibration for one wave type is a quite simple task which can be performed by recording the clamp load versus the time delay in a standard tightening test. The relation between the clamp load F and the time delay Δt for the elastic region is linear, only the slope of the curve has to be determined. Attempts are also known to determine the slope from physical material constants [3,5].

Due to the target of the investigations in the present study the calibration has to incorporate different levels of plastic deformation but it can neglect the elastic tightening path. So the calibration can be focused on the untightening behavior only.

In a pilot study it could be shown, that the slope of the untightening curve in Figure 6 as a first approximation is constant and independent of the level of the plastic deformation (Figure 8) for both wave types. The range for the longitudinal slope has been at 3.7% while the range of the transversal slope has been higher at 7.8%. The permanent elongation of the bolts has been varied up to 0.6%.

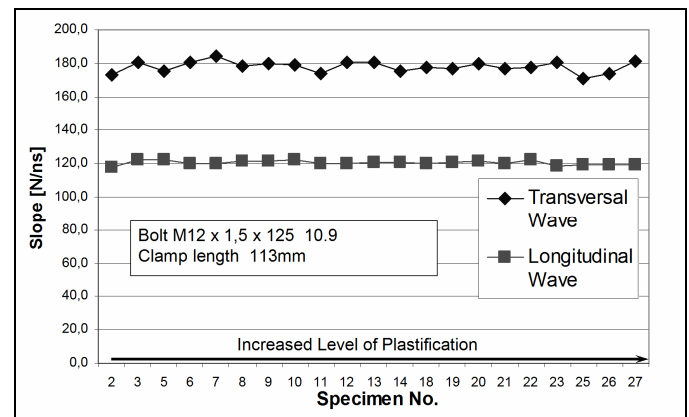


Figure 8: Slope of the untightening curves for different levels of plastification

This finding facilitates the calibration significantly. It can be assumed, that the untightening curves in Figure 6 are shifted to the right depending on the level of plastic deformation.

In a second step the untightening curves have been analyzed with respect to the relation between the load F for different levels of plastification and the time delay. For this task some discrete points have been selected. In fact for each level of plastic deformation one point on the untightening curve exists, where the untightening curves of both wave types intersect. For these points the clamp load as well as the time delay are equal for both types of waves which facilitates the analysis. Figure 9 demonstrates, that this relation can be described by a linear equation between the clamp load F and the time delay Δt with quite good correlation.

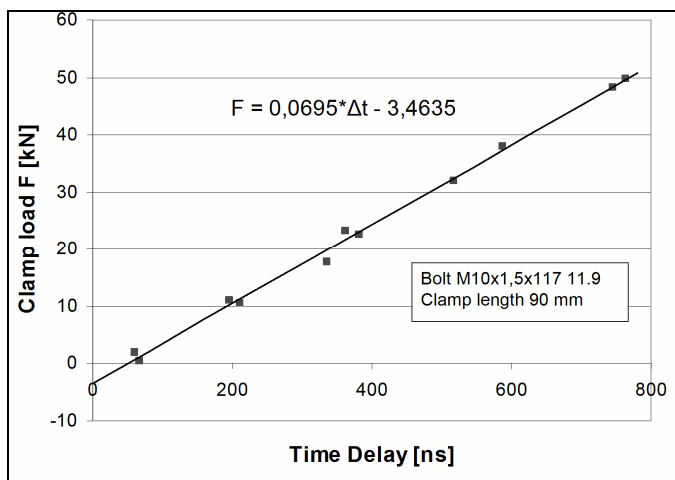


Figure 9: Regression analysis for the intersection points

Based on this finding a bilinear equation has been chosen to describe the load F in terms of the two different time delays:

$$F = C_1 \Delta t_L + C_2 \Delta t_T$$

The terms Δt_L and Δt_T represent the time delays actually measured during the test for longitudinal and transversal waves. They are defined as the time delay for the bolt under load versus the initial time delay for the virgin bolt which has to be recorded before the tightening of the bolt. It is also understood that this equation is used for the determination of residual loads only. It is not intended to describe the loading path of the tightening process.

The constants C_1 and C_2 can be determined easily from some discrete data points of the unloading curves. For the present study the intersection points have been used for the determination. Even two data points would be sufficient to mathematically determine the two constants, more points have been chosen to perform an average calibration.

RESULTS

Several tests with different configurations have been carried out to investigate the usability of this method in detail. So far the following results have been achieved.

Several bolt configurations have been used to perform a statistical test of the accuracy. After the necessary calibration at different levels of yield for each configuration a couple of virgin bolts have been tightened in the test-rig shown in Figure 7. The rig mainly consists of two Aluminium fillers which are used to get the required clamp length. A piezo load cell is positioned in the middle of the joint. To eliminate the influence of a non-uniform load distribution, hardened and ground steel plates are used to enclose the Aluminium fillers. To incorporate the influence of thermal elongation the test-rig has been exposed to 150°C for 5 hours and cooled down to room temperature to simulate a real engine application as close as possible. The residual clamp load was measured using ultrasonics as well as the integrated load cell.

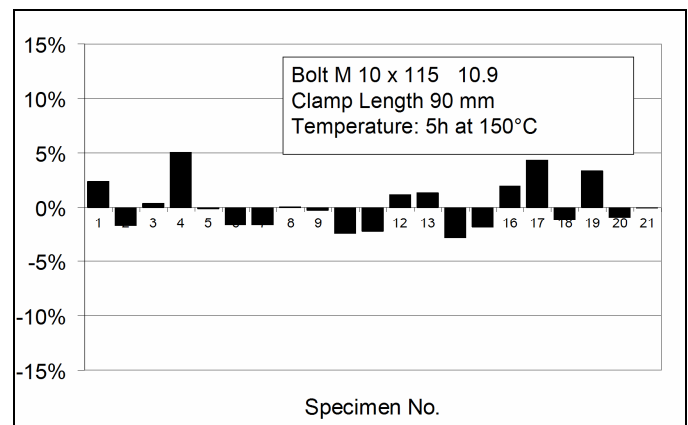


Figure 10: Deviation of the ultrasonic residual bolt load vs. load cell for an M10 x 115 mm bolt.

Figure 10 shows the accuracy for an M10x115 mm bolt of grade 10.9. 21 specimen have been tested. The maximum deviation (range) from the clamp load of the load cell was about +/- 4% (Figure 10). A load of about 55 kN had been measured after tightening. The range for the residual bolt load was 45 to 47 kN, the loss of clamp load after the temperature cycle about 16 to 18%.

Figure 11 shows the deviation reached for a con rod bolt M8x41 mm. A load of about 42 kN was measured after the tightening while the residual load after the temperature cycle dropped by around 14%. The maximum deviation of the ultrasonic measurement is about +/- 9%. Taking into account that the total loss of clamp load is around 14%, it is considered that this accuracy is not satisfactory.

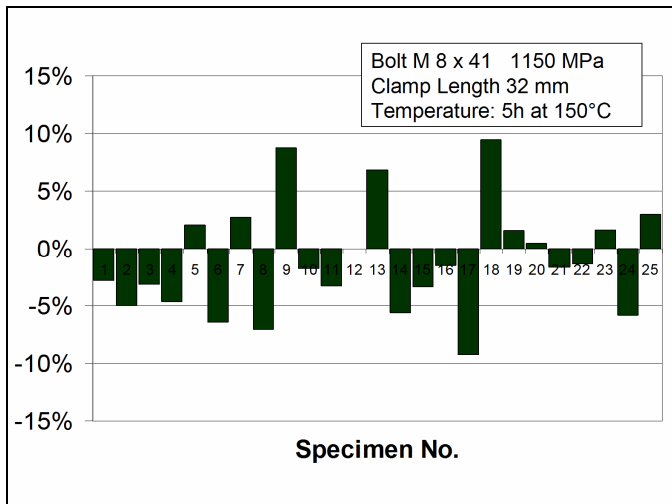


Figure 11: Deviation of the ultrasonic residual bolt load vs. load cell for an M8 x 41 mm bolt

Further Tests with different configurations and clamp lengths have led to the following results:

The accuracy increases for longer clamp length which is not surprising as this is a well known fact even for measurements in the elastic region. Any changes in the bolt stress or elongation lead to higher changes in the ultrasonic time delay which consequently leads to a better accuracy.

The accuracy decreases for higher levels of plastic deformation.

The yield strength has no significant influence on the accuracy. Tests have been performed with bolts that have been heat treated to different yield strength (900 MPa versus 1070 MPa). The same calibration data could be used without losing accuracy.

It has been found that the accuracy is significantly better for bolts that have the thread rolled after heat treatment versus bolts that are rolled before heat treatment. Thread rolling not only induces residual stresses in the thread, it also locally work hardens the material in the root of the thread. These changes in the microstructure are rolled back for bolts that are heat treated after thread rolling. It is assumed that the microstructure has an influence on the ultrasonic sound field.

So the current approach using a bilinear equation to describe the bolt load as a function of the time delays of both waves has proven the general concept. It is assumed that a further refinement of the equation e.g. using second order equations will increase the accuracy.

CONCLUSION

Real time ultrasonic clamp load measurement is a sophisticated method for the nondestructive analysis of bolted joints. It allows to track the clamp load during the whole tightening process. The concurrent use of longitudinal as well as transversal waves in principal allows to determine the residual clamp load of bolts that have been tightened into the yield without disassembling the joint. However the simple bilinear calibration function as used in this study may not satisfy the accuracy needed for most applications. So further refinements of the calibration method have to be carried out to improve the accuracy of the method.

ACKNOWLEDGMENTS

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