
ACOUSTIC METHODS

Preload Detection System Based on Ultrasonic Energy Transmission for Attached Joint Structures

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Abstract—In the aerospace industry and nuclear power plants, bolt preload is a crucial metric for assessing the quality of installation and the state of service of the flange connection parts of pressure vessels. The primary technique for determining the preload force is the ultrasonic stress measurement method based on pulse time-of-flight. However, the current ultrasonic preload measuring approach is no longer applicable for unique bolted structures like pointed bolts and high acoustic attenuation bolts, as it is unable to receive the bolt end face echo. This work aims to address this issue by proposing a detection system based on interlayer ultrasonic energy transfer-based bolt preload measurement method. The ultrasonic energy transmission model of the sandwich's rough interface is built using both classical contact theory and ultrasonic propagation theory. When paired with a finite element simulation, this model shows a linear relationship between the sandwich's ultrasonic transmission signal energy and the bolt preload force. The relationship between the ultrasonic transmission energy and the bolt preload force under the ultrasonic frequency contact surface roughness and other factors was systematically investigated. A testing platform was set up to conduct the ultrasonic energy transmission test on the preload force of the bolt interlayer. According to the test results, there is a good linear relationship between the ultrasonic transmission signal energy and bolt preload obtained under various groups of parameters, R^2 is greater than 0.97, and the bolt preload measurement error range for flange bolts is between -5.4% and 5.6% . These findings suggest that the method presented in this paper has a promising future.

Keywords: bolts, preload, ultrasonic testing, energy transmission, roughness

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1. INTRODUCTION

The aerospace industry and nuclear power facilities frequently employ bolting as a connection mechanism for reactor flanges because of its high connection strength, dependability, ease of installation, and simplicity of disassembly [1, 2]. By preventing gaps or relative slippage of the connected parts after loading, the axial force on the bolts works on the connected parts to improve the tightness and reliability of the connection and, ultimately, ensure the reliability of the connected parts [3–5]. The complex and variable working conditions that the bolt connection structure faces frequently result in a decrease in the bolt connection joint's preload, which loosens the joint surface and causes slippage, noise, and other faults that impair the connection's reliability [6, 7]. Consequently, one of the most important aspects of ensuring the security of flange bolted connections in nuclear power plants is to keep an eye on the preload of high-pressure bolts both during installation and operation [8, 9].

The acoustoelastic action of ultrasound, the utilization of acoustic wave speed, and the link between stress and preload are the foundations of the ultrasonic method, an efficient non-destructive testing technique for determining bolt preload [10–12]. Qingchao Sun et al. developed a piezoelectric ceramic transducer that can be embedded in a particular bolt head to detect bolt preload ultrasonically. This eliminates

the probe coupling's impact on the test object's surface and improves measurement accuracy compared to using a conventional ultrasonic probe [13]. The non-contact character of electromagnetic ultrasound removed the influence of coupling agents and decreased measurement error. Xu Ding et al. used an electromagnetic ultrasound transducer to obtain both longitudinal and transverse wave data concurrently [14]. With a lower measurement error than the longitudinal and transverse wave method, Xi Li et al. measured the axial stress of bolts by measuring the traveling wave acoustics generated by the longitudinal and transverse wave modal transitions using an electromagnetic ultrasonic transducer [15]. In order to prevent the coupling thickness of the liquid coupling agent and the corrosion of the structural surface from affecting the ultrasonic measurement accuracy, Yongmeng Liu et al. designed a dry-coupling measurement device [16]. This resulted in a 1% increase in measurement accuracy over traditional liquid coupling. In order to achieve high-precision measurement of axial load under various clamping lengths, Xuechao Jing et al. prepared a piezoelectric thin film sensor on the bolt end face using a vapor deposition method and corrected the difference between the effective stress length and the actual clamping length by experimental study [17]. Xin-Xin Zhao et al. developed a more precise technique for determining the axial force of in-service bolts by utilizing the principle of acoustic elasticity to correct the effects of temperature and bolt elastic deformation on the acoustic velocity under the action of an external force through experiments and calculations [18]. Based on the theoretical consideration of local deformation of connecting parts caused by mechanical load and temperature, Lee Eun-Song et al. developed a calibration equation applied to various types of bolts and achieved the findings through tests with an error of 8.8% [19]. In conclusion, there are more results when using the ultrasonic method to detect bolt preload. However, because the current methods of ultrasonic detection all require direct measurement of the bolt, they cannot be used on pointed bolts or bolts with high acoustic attenuation coefficients because of their unique structural and material properties, which prevent the ultrasonic signals from being measured at the time of flight [20–22].

In order to tackle this problem, a system for measuring bolt preload is built based on piezoelectric active sensing technology, which transmits the initial wave energy of signal through ultrasonic wave in bolted connection structure. The effects of various ultrasonic frequencies, the roughness of contact surfaces of various connection structures, and the preload states of multiple bolts on the transmitted signal energy were systematically studied through theoretical analysis, finite element simulation, and test verification. A bolt preload detection system based on the ultrasonic transmission energy of sandwich structures was built.

2. METHODOLOGY PRINCIPLES

The G-W theory [23] describes the micro-convex model of random rough surface contact, analyzes the micro-convex's stress deformation law, and establishes the relationship between the stiffness of the contact surface and the preload force and the joint structure's actual contact area. The actual contact area is the region of the contact surface that is actually in contact between the microscopic structures when two machined parts come into contact. All machined surfaces are non-smooth on a microscopic scale. This has an impact on the ultrasonic propagation process at the interface because the real contact area is much lower than the theoretical contact area estimated from the geometry. The actual contact area varies with the pressure applied to the contact surface because metal materials bend elastically. Through theoretical calculations and numerical simulations, Wu [24] et al. came to the conclusion that, in a bolted joint structure, the bolt preload and the normal load in the main area have a proportionality that is between 99 and 99.5%. This means that, when tightening bolts are used to preload bolts, the load on the contact surface increases synchronously, increasing the actual contact area. The relationship between the bolt preload and the actual contact area is linear.

The reason why ultrasonic waves go from the excitation source to the sandwich 2 (medium 2) is because the two media's actual contact surface is made up of interconnected microscopic morphological features and gaps. Sound waves will be reflected and transmitted at the interface due to the differences in the acoustic impedance of the sandwich material that makes up the gap and the air. When an ultrasonic wave is fired vertically from one side of the sandwich to the contact surface, some of the wave will diffuse through the interface and end up being received by the probe. This is known as the transmitted wave, and its energy can be calculated using P_t or I_t ; the remaining wave will be reflected at the interface's surface, which is known as the reflected wave, and its energy can be calculated using P_r or I_r . Figure 1 displays the directions of energy conduction for incident, transmitted, and reflected waves. The energy distribution between these three types of waves satisfies the following boundary requirements, and it is dispersed in accordance with the sound pressure, transmittance, and reflectance of the sound intensity:

- (1) There is an equal amount of pressure on both sides of mediums 1 and 2.
- (2) The mass locations on both sides of mediums 1 and 2 have equivalent vibration velocity amplitudes.

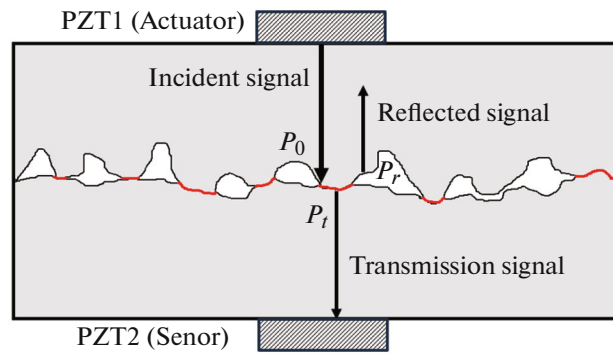


Fig. 1. Transfer of energy at the microcontact interface.

The energy distribution of sound waves that are reflected and refracted in various mediums is significantly influenced by acoustic impedance. The quantitative relationship between sound pressure and sound intensity at the interface is typically expressed using the sound pressure reflectivity (r), sound intensity reflectivity (R), sound pressure transmittance (t), and sound intensity transmittance (T). The following relationship exists between the two media's acoustic impedances and the reflectance of sound pressure and intensity:

$$r = \frac{P_r}{P_0} = \frac{z_2 - z_1}{z_2 + z_1}, \quad (1)$$

$$t = \frac{P_t}{P_0} = \frac{2z_2}{z_2 + z_1}, \quad (2)$$

where P_0 is the incident wave sound pressure, P_r is the reflected wave sound pressure and P_t is the transmitted wave sound pressure.

$$R = \frac{I_r}{I_0} = \frac{\frac{P_r^2}{2z_1}}{\frac{P_0^2}{2z_1}} = \left(\frac{z_2 - z_1}{z_2 + z_1} \right)^2, \quad (3)$$

$$T = \frac{I_t}{I_0} = \frac{\frac{P_t^2}{2z_2}}{\frac{P_0^2}{2z_1}} = \frac{4z_2z_1}{(z_2 + z_1)^2}, \quad (4)$$

where I_0 is the sound intensity of the incident wave, I_r is the sound intensity of the reflected wave and I_t is the sound intensity of the transmitted wave.

The acoustic pressure reflectivity and acoustic intensity reflectivity will increase with a large difference in acoustic impedance, which will result in more energy being reflected by the ultrasonic wave. Conversely, when the acoustic impedance is close to the same, the ultrasonic wave is almost completely transmitted and there is no reflected wave. This is demonstrated by the above formula. As a result, when the ultrasonic wave travels through the bolted structure, it is nearly entirely reflected in the region where the rough surface and the actual void are in contact, and nearly entirely transmitted in the portion of the rough surface where the contact actually occurs.

Ultrasonic energy transferred at the sandwich's interface:

$$E = 0.5\rho VS_0fP_t^2, \quad (5)$$

where E is the transmitted ultrasonic energy, ρ is the medium's density, V is the ultrasound's speed of propagation in the medium, f is its frequency, P_t is the transmitted wave's sound pressure, and S_0 is its propagation area and it is positively connected with bolt pretightening force. As such, the actual contact area of the sandwich interface is linearly proportional to the bolt preload, and the ultrasonic energy deliv-

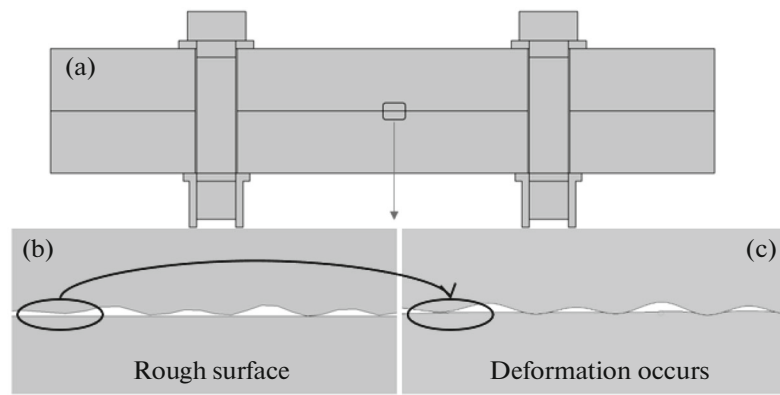


Fig. 2. Finite element model. (a) Simulation model. (b) Surface of microscopic contact. (c) Contact surface deformation caused by load.

ered through the interface is parallel to this relationship. Because the bolt preload is linearly connected to the transmitted energy, raising it will allow the ultrasonic waves to flow through the sandwich structure with less energy loss.

3. ANALYSIS OF SIMULATIONS

In order to assess the change in ultrasonic energy that penetrates the rough interface under various bolt preloads, the propagation process of ultrasonic waves in the bolted joint structure is numerically simulated using finite element simulation.

The model's alloy steel bolt measures 55 mm in length and 9.8 mm in diameter, is made of 0Cr13Ni8Mo2Al. The plate is made of aluminum alloy 7075 and is 70 mm in length and 15 mm in thickness. Preload forces range from 0 to 20 kN, and they are applied to every bolt. The solid mechanics module is used to determine the preload force. Ultrasound is calculated using circuits, power supply, solid mechanics, and pressure acoustics. To lessen echo signal interference, the model's external border is designed as a soft sound field. We mimic an ultrasonic probe with a 10 mm diameter by setting the normal acceleration of the border. Figure 2 illustrates the micro convex body structure's deformation process under normal stress on the rough interface. Figure 3 illustrates the sent signal waveform and the ultrasonic signal propagation process at the joint surface.

The mesh in the simulation model is split into triangles, has an ultra-fine setting, is between 0.5 and 1 μm in size, and has an ultrasonic frequency of 1 MHz. Figure 2 illustrates how the bolt preload's normal load on the contact surface will cause the rough contact surface's microstructure to deform. This deformation will be shown as an increase in the actual contact area between the upper and lower contact surfaces as well as a decrease in the gap. As illustrated in Figs. 3a and 3b, ultrasonic waves can be received on the opposite side of the joint during the propagation process in the joint surface of the real contact parts through, in the uncontacted parts of the gap reflection, through the joint surface of the ultrasonic signal. A typical transmitted signal received at a bolt preload of 20 kN is depicted in Fig. 3c. Based on the simulation results, Fig. 3d depicts the relationship between the transmitted signal energy and the bolt preload. It is important to note that the transmitted signal energy in Fig. 3d is not an absolute value; rather, it is given as the square of the ultrasonic primary wave's amplitude. According to the simulation results, there is a usual linear relationship between the bolt preload and the intensity of the ultrasonic transmission signal, indicating the feasibility of monitoring bolt preload based on energy transmission.

4. BOLT PRETENSION FORCE DETECTION SYSTEM UTILIZING ULTRASONIC ENERGY TRANSFER

4.1. Evaluation Platforms

A test system platform was constructed based on the idea of measuring the bolt preload of the connected structure via ultrasonic energy transfer. Figure 4 illustrates the test system's premise, and Fig. 5 shows the test system device.

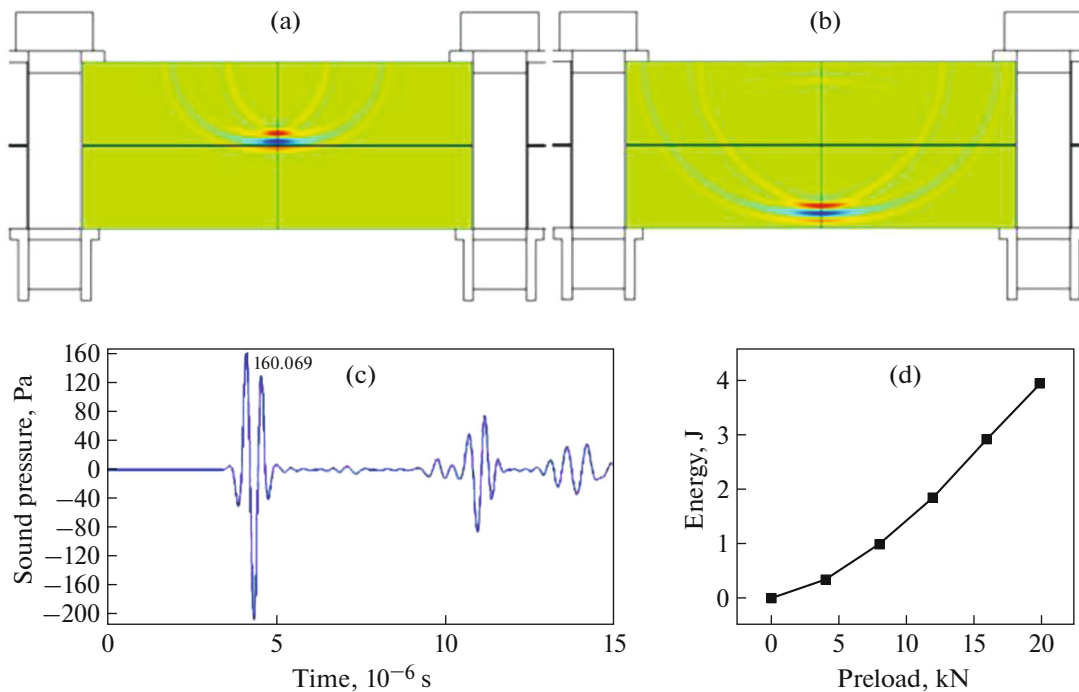


Fig. 3. Results of the simulation analysis. (a) The propagation process of ultrasonic waves at $t = 3.5 \mu\text{s}$. (b) The propagation process of ultrasonic waves, $t = 6 \mu\text{s}$. (c) A signal that was sent. (d) Bolt preload force and transmitted signal energy (J) relationship.

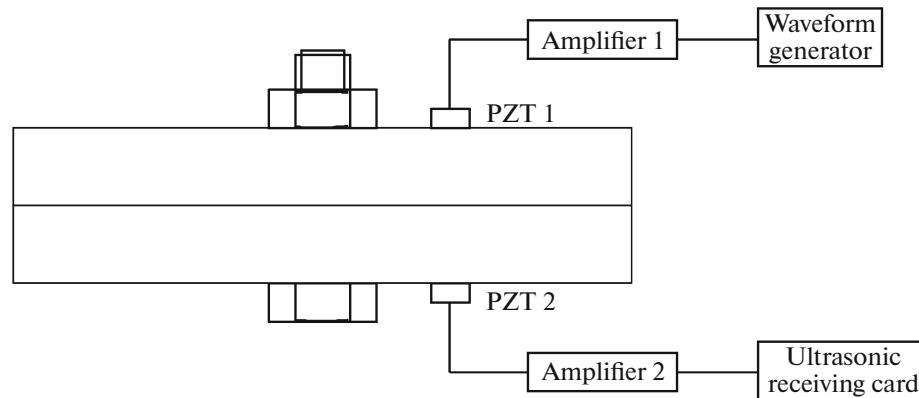


Fig. 4. Bolt pre-tightening force measurement test system schematic.

The primary components of the test system's hardware are equipment for ultrasonic excitation, signal amplification and receiving, bolt preload, and preload force measurement. The ultrasonic signal received at the opposite point on the other side is similarly amplified before being finally received by the acquisition card. The electrical signal produced by the waveform generator is amplified and then excited on one side of the connector through the piezoelectric transducer.

The DG992 arbitrary waveform generator produces the ultrasonic waves, it can modulate burst period, waveform, and ultrasonic frequency, among other parameters; the acquisition card's sampling frequency is 250 MSa/s; the piezoelectric transducer's center frequency is 0.5, 1, and 2 MHz; and the wafer diameter is 10 mm.

The plate connection sample is made of 7075-T6 aluminum alloy, measures $200 \times 40 \times 15 \text{ mm}$, and has a 10 mm diameter through hole that is processed in the 100 mm plate length and 20 mm plate width

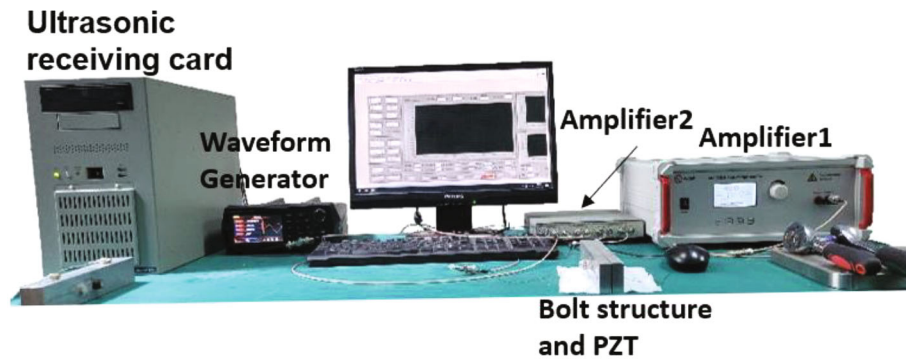


Fig. 5. Test apparatus.

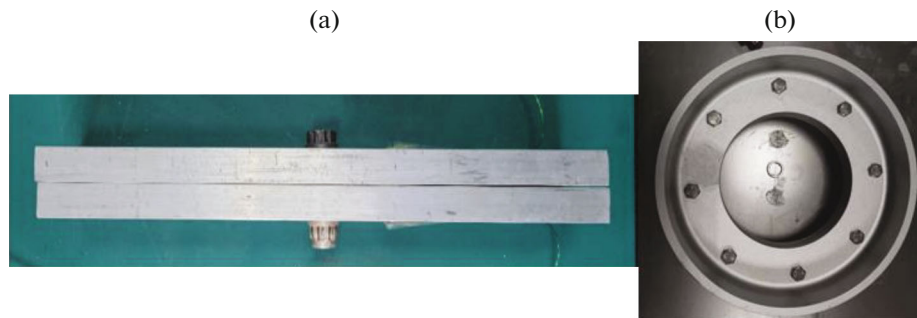


Fig. 6. Test specimen. (a) A bolted specimen simplified, (b) A specimen with simplified flanges.

directions. The plate samples are separated into three pairs, and their joint surface roughness readings are 0.8, 3.2, and 12.8 μm , appropriately, as shown in Fig. 6a.

Flange simulation body with identical scale reduction, material (7075-T6 aluminum alloy), joint surface roughness (3.2 μm), bolt hole diameter (10 mm), hole number 8, center distance (236 mm), thickness (15 mm), and outer and inner diameters (300 mm and 172, respectively), as shown in Fig. 6b.

The 50 mm-long, 0Cr13Ni8Mo2Al bolts used in the testing had piezoelectric plating on their heads, which stimulated and converted ultrasonic waves. The calibration test was finished in order to determine the bolts' permitted preload of 19.8 kN based on the ultrasonic longitudinal wave's sound time.

Prior to the initiation of every test set, the piezoelectric sheets were fastened to both connector sides in order to prevent movement and to prevent the coupling layer thickness from changing. Figure 7 depicts typical ultrasonic transmission signals.

4.2. The Method of Experimentation

In order to confirm the correctness of the data, nine sets of measurements were done, each having at least two repeats. Three types of roughness and three distinct frequencies of piezoelectric wafers were employed in the experiments.

The following is the procedure for calculating ultrasonic transmission energy:

To measure the ultrasonic transmittance energy in this group, load the bolt preload in multiple steps using the torque wrench. After each loading, the preload force of the bolt is measured instantly until it is loaded to about 20 kN. Once the preload is finished, the preload force of the bolt is unloaded until it reaches 0 kN. Every time the preload force is measured, a group of three ultrasonic transmitted signals is collected. The ultrasonic sound is excited on one side of the connector through the piezoelectric sheet, and the transmitted ultrasonic signal is received at the opposite position on the other side.

As illustrated in Fig. 8, the ultrasound transmission signal received is processed, the start wave signal is intercepted, and the signal energy is computed.

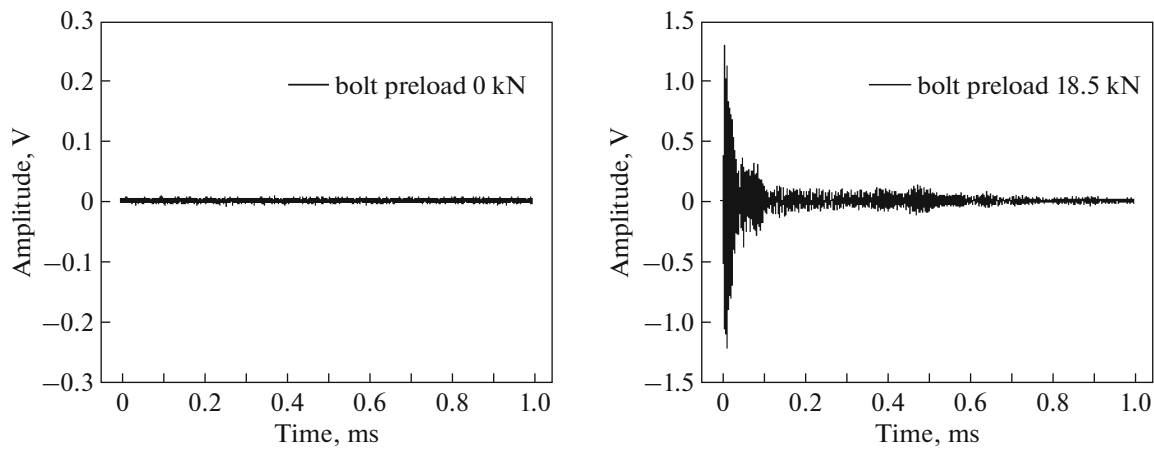


Fig. 7. Typical signals used in ultrasonic transmission, preload of 0 kN (a) and 18.5 kN (b).

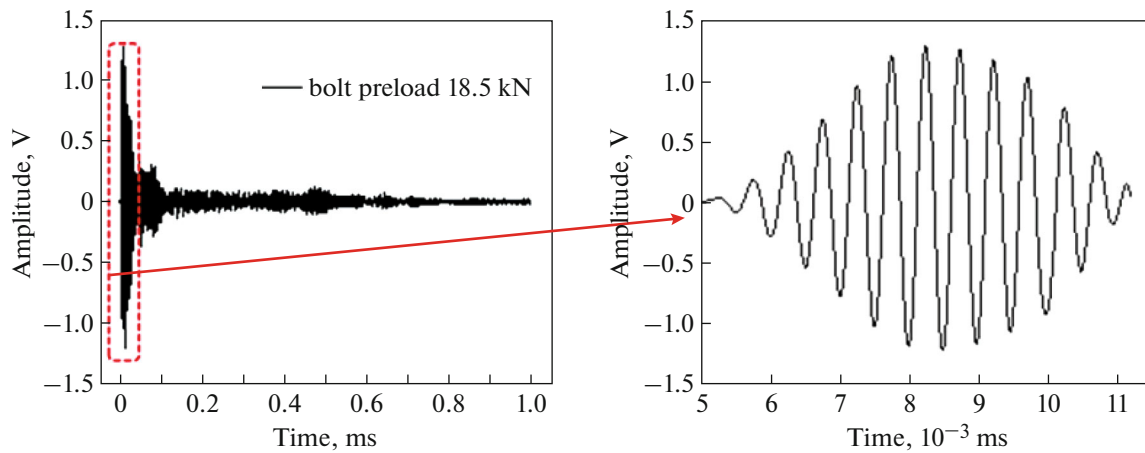


Fig. 8. First wave signal and ultrasonic transmission signal received.

5. RESULTS AND DISCUSSION

The transmission signal of ultrasonic waves on the bolt connection interface is measured in the test procedure of bolt preload measurement based on ultrasonic energy transmission by varying the contact interface roughness and ultrasonic frequency of the cylindrical joint. The sent signal of the start wave is recovered after the transmitted signal has undergone wavelet transform noise reduction processing. The projected signal energy was determined by averaging the squares of the respective amplitudes at each sampling point in the intercepted signal. This was done because the energy of the acoustic signal is directly proportional to the square of the amplitude. The relative energy of the projected signal is shown against the bolt preload force for an array of test data with the identical test conditions. The energy of the related transmitted signal is taken as 100% when the bolt preload force is loaded to its highest value.

Figure 9 displays the outcomes of bolt preload detection and ultrasonic transmission energy for various piezoelectric sheet frequencies, and Table 1 are the statistical results. Each data set's maximum value is utilized as a 100% reference value for creating Fig. 9, and the remaining data is compared to this value, to more clearly illustrate the connection.

Figure 9 illustrates how increasing bolt preload causes an increase in the transmitted ultrasonic energy in the bolted joints. Among the tests conducted on connection specimens with contact surface roughness R_a of 0.8 and 3.2 μm , the R^2 value of the resulting transmitted signal energy is about 0.99 after a straight-line fit to the bolt preload data, showing a good linear relationship, as shown in Tabel 1. The fitted straight lines plotted using the ultrasound data at frequencies of 2 and 1 MHz in the test on the connection specimen with a contact surface roughness R_a of 12.8 μm showed a low degree of linearity, with an R^2 value of

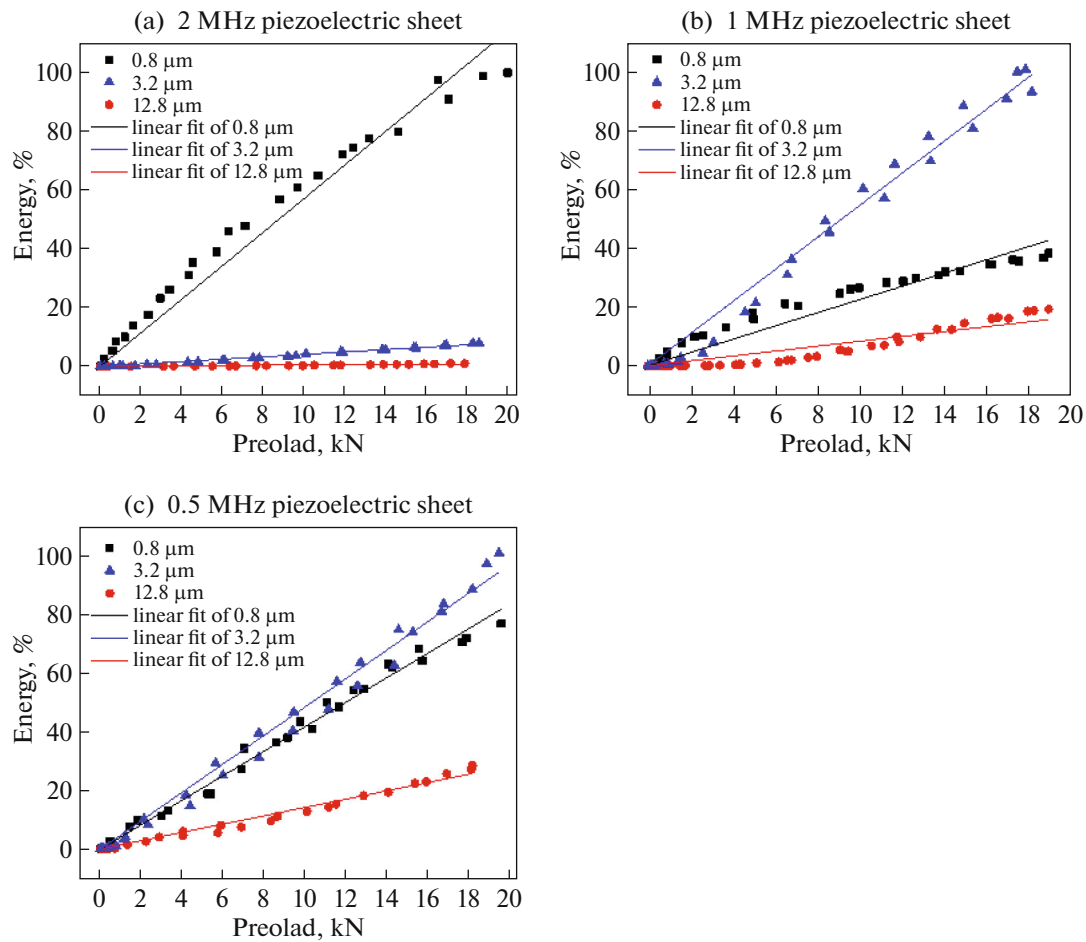


Fig. 9. Test findings for the piezoelectric sheet's ability to project ultrasound waves at various frequencies and bolt pre-loading force. (a) 2 MHz piezoelectric sheet; (b) 1 MHz piezoelectric sheet; (c) 0.5 MHz piezoelectric sheet.

approximately 0.91; in contrast, the fitted straight line plotted using the ultrasound data at a frequency of 0.5 MHz showed a very high degree of linearity, with an R^2 value of 0.99. Moreover, experiments were carried out on a sample with a Ra roughness of 0.8 on the contact surface using a 2 MHz ultrasonic piezoelectric crystal, and the transmitted signal obtained was the strongest among the three groups of varied roughness samples. In the ultrasonic detection experiment group, the effect of roughness change on the

Table 1. Statistical result of the test

Ultrasonic frequency (MHz)	Contact surface roughness Ra (μm)	Linear relationship between transmitted energy Y and preload X (kN)	Determination coefficient R^2
2	0.8	$Y = 5.17X \times 100\%$	0.990
2	3.2	$Y = 0.0615X \times 100\%$	0.986
2	12.8	$Y = 0.367X \times 100\%$	0.943
1	0.8	$Y = 2.27X \times 100\%$	0.989
1	3.2	$Y = 1.27X \times 100\%$	0.981
1	12.8	$Y = 5.40X \times 100\%$	0.937
0.5	0.8	$Y = 4.15X \times 100\%$	0.996
0.5	3.2	$Y = 4.82X \times 100\%$	0.995
0.5	12.8	$Y = 1.41X \times 100\%$	0.952

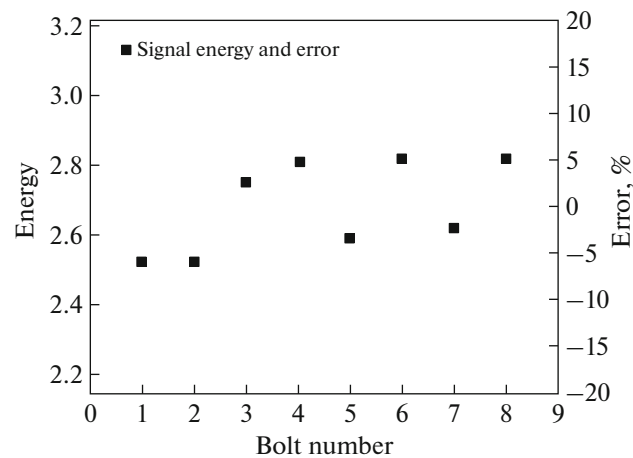


Fig. 10. Flange bolt preload and ultrasonic transmission signal energy at different parts of the flange.

transmitted signal intensity at a frequency of 1 MHz is smaller, with the difference being within 5 times; when the frequency is lowered to 0.5 MHz, the difference between the detection results of the different roughness samples is further reduced to within 3 times. The signal energy at the same preload is more than 10 times that of the other two roughness samples. Touch will happen when rough surfaces come into touch and the microstructure of the contact surface deforms more than the space between the structures. These contact surfaces allow the ultrasound to go through and enter the other medium. Ultrasonic waves can, however, avoid openings, flaws, and other features that are smaller than their wavelength during propagation. Therefore, when the contact surface's roughness is clearly raised, the signal strength that can pass through and avoid the detecting object is quickly decreased utilizing the high-frequency ultrasonic transmission method. The transmitted energy is insensitive to a low-roughness surface if the ultrasonic frequency is low.

Eight bolts on the flange specimen were sequentially subjected to an 18 kN preload force. The ultrasonic transmission signal energy in the neighboring region of each bolt was measured and the results are shown in Fig. 10. In Fig. 10, the ordinate energy unit here is J, by comparing the data collected using this method with the preload force's base value, the error is determined. The transmitted signal energy for each bolt of the flange, as shown in Fig. 10, is within -5% to 6% of the error of the transmitted signal energy when compared to the linear law shown in Fig. 9. As a result, by measuring the ultrasonic transmitted signal energy in the bolt's surrounding region, the preload of the bolt can be determined.

6. CONCLUSIONS

This paper presents the design of a sandwich ultrasonic energy transmission-based bolt preload detecting system to solve the problem of ultrasonic preload measurement of pointed bolts and bolts with high sound attenuation.

(1) A linear relationship between the wave energy propagating through the interface and the bolt preload is demonstrated using finite element simulation analysis.

(2) Install a system for detection, using laminated ultrasound as a means of energy transfer, the impacts of piezoelectric sheet frequency and roughness on bolt preload measurement findings were methodically examined. The transmitted energy is insensitive to a low-roughness surface if the ultrasonic frequency is low; conversely, when the specimen's contact surface is rougher, the results obtained using a lower frequency piezoelectric sheet are more accurate.

(3) The measurement error of each bolt connection component is within $-5\%\sim 6\%$ when this system is used to measure the preload force of the flange bolt group, which can satisfy the engineering application.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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