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Damage detection in a bolted lap joint using guided waves

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Abstract

The paper presents the experimental investigation of guided waves application to the condition assessment of prestressed bolted connections and a concept of new quantitative indicator. The main goal of the research was the analysis of the influence of the contact conditions changes to the characteristics of a propagating disturbance. The experimental tests were carried out for a single bolted lap joint. The excitation and acquisition of elastic waves were performed using piezoelectric plate transducers. The measurements were performed for the gradually increased value of the bolt load, which was controlled by the force washer transducer. The results of tests show the occurrence of relationship between the recorded signals amplitudes or the phase shifts and bolt load values only in initial time period. Therefore, the quantitative analysis of recorded waveforms was performed in the frequency domain based on the power spectral moment theory. Additionally the concept of the modified power spectral moment taking into account the guided wave frequency characteristic has been introduced. The results indicated the possibility of the use of higher order modified power spectral moments for evaluation of the bolted joint condition.

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Keywords: structural health monitoring; damage detection; guided wave propagation; bolted lap joint.

1. Introduction

Elastic wave propagation is one of the most frequently used physical phenomenon in the non-destructive testing. This method was successfully used in detection of many types of damage in steel structural components, e.g. cracks in plates [1], corrosion of tendons [2] or defects in pipes [3]. Nowadays, elastic waves are also becoming more increasingly applied in monitoring systems of various connections types, especially bolt joints. So far, several

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different bolted joints diagnostic strategies based on the pattern recognition [4], the support vector machines [5], the acoustic moment, the second harmonic generation [6], the signal energy [7] or the signal cross-correlation [8] have been developed. However, a growing number of the bolted joints applications result in the need to development and improvement above mentioned techniques.

The aim of this study is to analyse the possibilities of using the quantitative indicator based on the concept of the modified power spectral moment and propagation of guided waves for the assessment of the state of a bolted connection. The paper presents a case study analysis conducted on the example of a single lap bolted joint.

2. The concept of the modified power spectral moment

The methods for detecting damage of bolted connections are used mainly with quantitative indicators. One of approaches is application of power spectral moments which are defined in the frequency domain, according to the equation [9]:

$$M_n = \int_o^{f_N} f^n W(f) df, \tag{1}$$

where f – frequency, n – the power spectral moment order, $W(f)$ – power spectral density function, f_N – Nyquist frequency. The power spectral moments determine the power spectral density distribution about the zero frequency. This methodology is widely used in non-destructive testing of non-linear and non-homogeneous structures [9], where due to the interaction with damage unclear and intricate waveforms can be registered. For similar reasons, this approach is also useful for bolted joint diagnostics because the initial waveform during passing the contact zone is distorted and multiplied as a result of reflections from free edges of jointed elements. In order to adapt the approach base on the power spectral moments, the additional parameter f_0 referring to the central frequency of the excitation wave was added. As a result of modification Eq. (1) takes the following form:

$$\bar{M}_n = \int_o^{f_N} (f - f_0)^n W(f) df. \tag{2}$$

The modified power spectral moments specify the energy distribution about the central frequency and they are a measure of the wave dispersion.

3. Experimental set-up

The object of experimental investigations was a laboratory model of a single lap joint. The joint was composed of two steel plates with dimensions 6 mm × 80 mm × 440 mm, one steel bolt with a diameter of 12 mm, one nut and two washers. All elements were assembled together (Fig. 1a) and installed in a steel frame to ensure a fixed position of steel plates. The increasing value of the bolt load was applied using a torque wrench. The tests were carried out using two independent systems. The bolt load was measured using the PCB force washer transducer and the LMS SCADAS data acquisition system. The registration and excitation of elastic waves were carried out by the PAQ-16000D device and piezoelectric transducers Noliac NAC2024 with dimension of 3 mm × 3 mm × 2 mm attached to the structure at selected points. The excitation point was localized at the distance of 10 cm from the axis of connection. An input wave packet was a five periods sine with a central frequency 100 kHz modulated by the Hanning window. The waves were measured with the use of six sensors (Fig. 1b) – two sensors (S1 and S2) were attached at the end of the first plate and the others (S3–S6) were spaced at a distance of 5 cm on the top surface of the second plate. The measurements were performed for gradually increased value of the pretension force in the bolt. During the measurements, the wave propagation signals were excited and registered, after each increase of the pretension force.

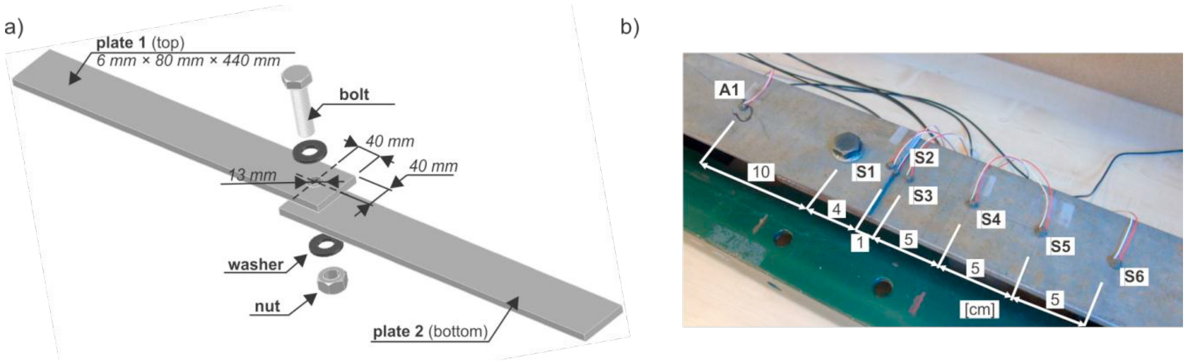

Fig. 1. (a) geometry of analyzed bolted joint; (b) transducers arrangement.

4. Results

The experimental results are presented in Figs. 2 and 3. The 2-dimensional maps shows the influence of the bolt load to the time-variability of the recorded signals. In the case of a sensor mounted at the end of the first plate, the significant value of transverse vibrations is observable only in the initial time period (Fig. 2a). In this part of the signal two different wave packet can be distinguish. The first one is associated with the symmetrical plate wave mode and the second with the antisymmetric mode. The amplitude of both wave packet decreases with the increase of the bolt load. In the case of the remaining sensors, located on the second plate, the value of the measured signal drops very slowly (Figs. 2b–d).

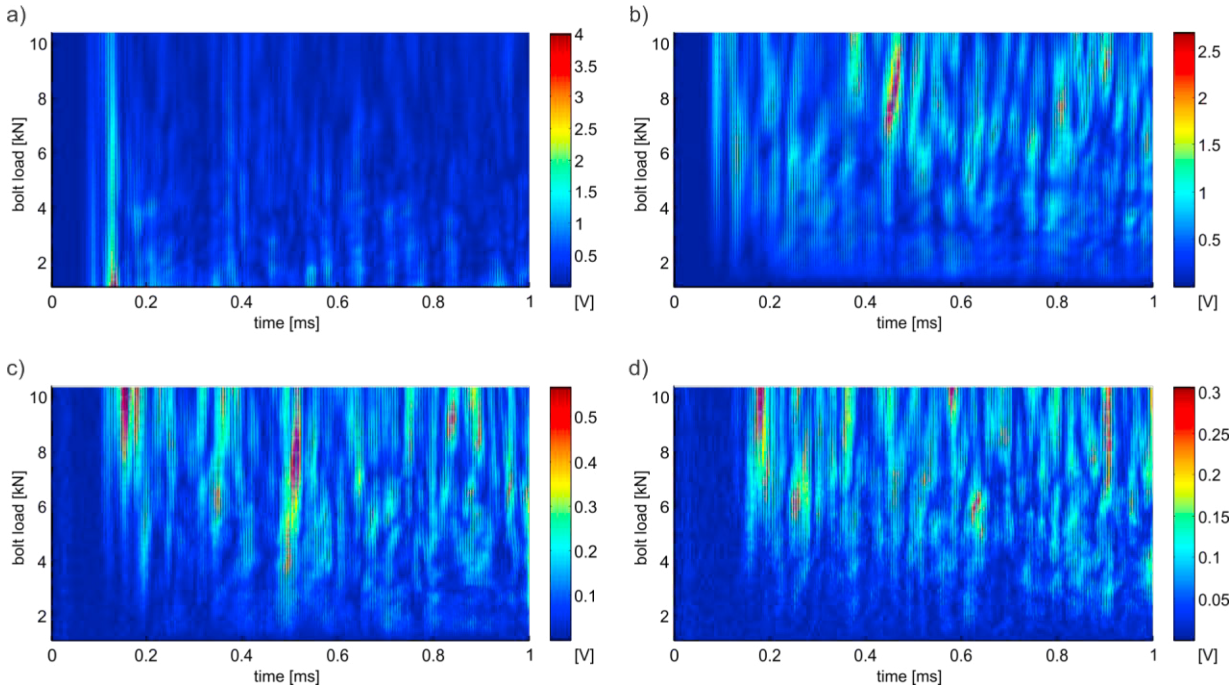

Fig. 2. Absolute value of the signal amplitude registered by sensor: (a) S1; (b) S3; (c) S5; (d) S6.

Figure 3a shows the signals registered by sensor S4 in the time domain. It can be seen that the increase of the bolt load is associated with an increase of the amplitude of the initial wave packet and with a small phase shift. However, in next time interval (0.15-0.3 ms) the trend is not maintained. As a result of wave reflections from free edges of the plate, the initial wave packet is multiplied. Additionally during propagation through the contact zone the wave is partially reflected and the mode conversion occurs. In the frequency domain the relationship between the amplitude of signal and the value of the bolt load is also indiscernible (Fig. 3b). As a result, the qualitative comparison of signals in wide time period is rather difficult.

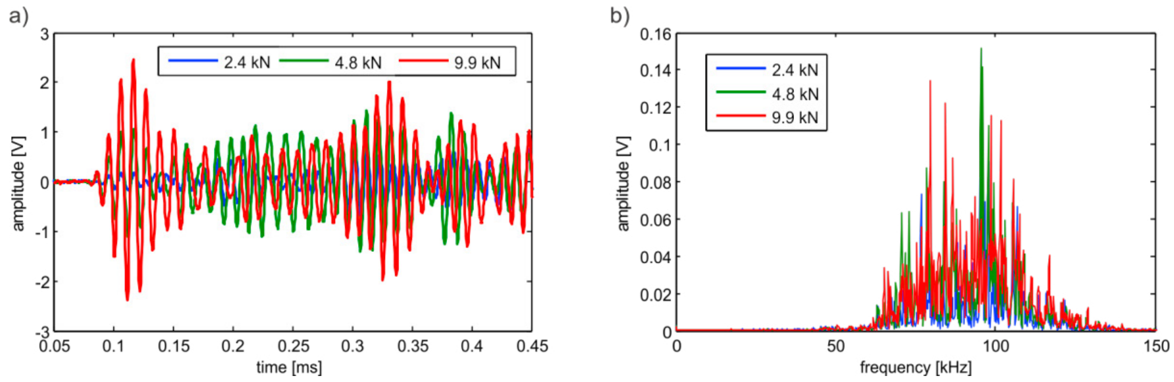

Fig. 3. Output voltage signal registered by sensor S4 for various values of the bolt load in: (a) time domain; (b) frequency domain

The normalized values of zero to third order spectral moments according to Eqs. (1) and (2) are plotted in Figs. 4–7. In case of zero order moments, the proposed modification does not affect the parameter values. The values of M_0 and $\bar{M}_0$ coincide with each other. It can be observed that there is a relationship between the bolt load and the zero order power spectral moment value. For most sensors it can be approximated by bilinear functions since there is the bolt load value above which the smaller increase or even decrease of M_0 is observed. A similar character has the variability of parameter M_1. The clear linear trend occurs in the case of the second order (Fig. 6) and the third order (Fig. 7) moments. In both cases the linear approximation of the normalized parameter is plotted on graphs by the dashed line. R^2 values of the parameters determining the correctness of the model fitting varies in the range of 0.905–0.984 for $\bar{M}_2$ and in the range of 0.931–0.974 for $\bar{M}_3$.

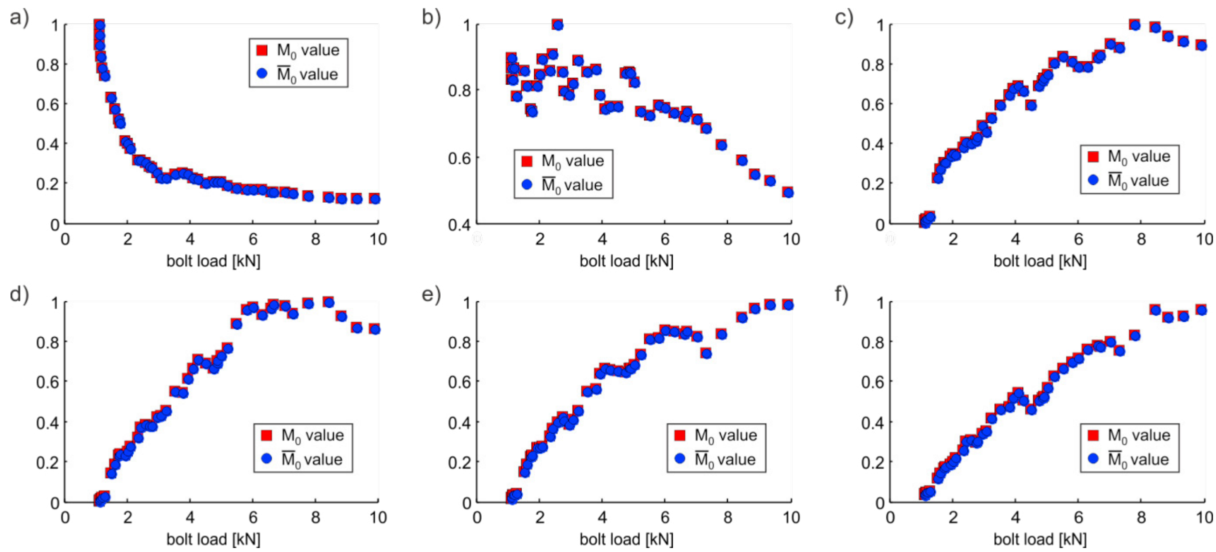

Fig. 4. The relationship between the bolt load and the zero-order power spectral moment calculated for the signal registered by sensor:
(a) S1; (b) S2; (c) S3; (d) S4; (e) S5; (f) S6.

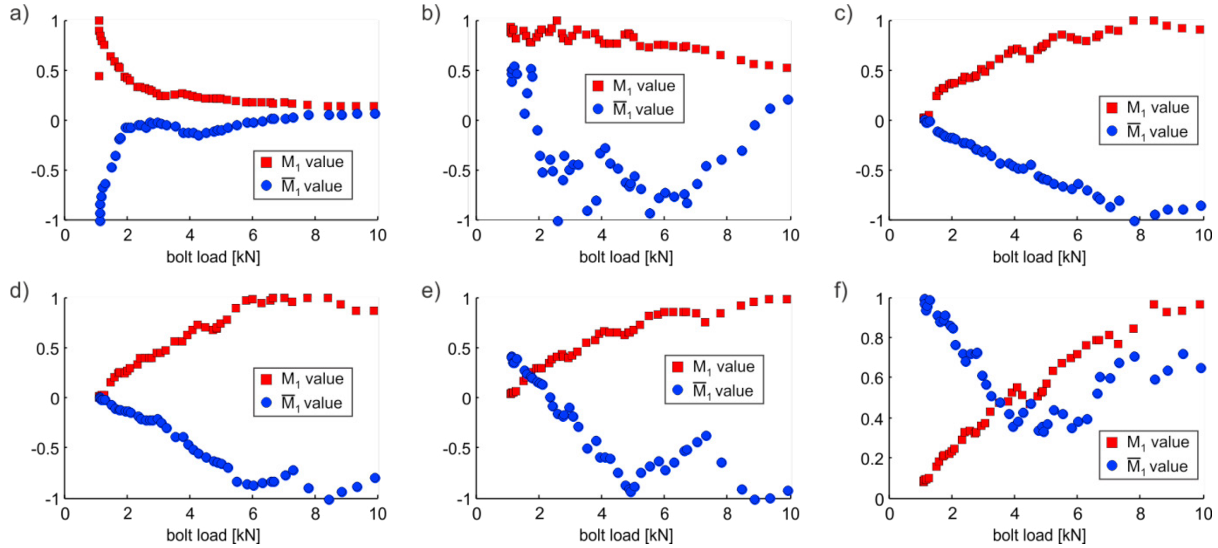

Fig. 5. The relationship between the bolt load and the first-order power spectral moment calculated for the signal registered by sensor: (a) S1; (b) S2; (c) S3; (d) S4; (e) S5; (f) S6.

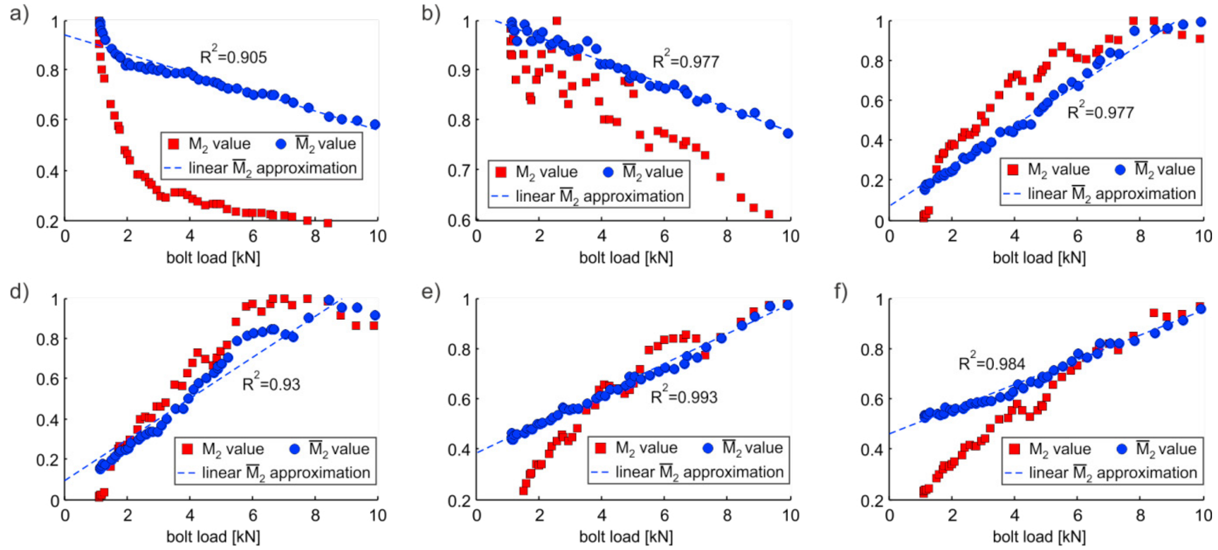

Fig. 6. The relationship between the bolt load and the second-order power spectral moment calculated for the signal registered by the sensor: (a) S1; (b) S2; (c) S3; (d) S4; (e) S5; (f) S6.

5. Conclusions

In this paper the concept of the use of elastic wave propagation and the modified power spectral moment for the assessment of the state of the bolted lap joint was presented. The research was focused on quantitative changes of the registered signals in the frequency domain. It has been shown that taking into account the central frequency of the excitation signal allowed to determine the linear trends in relationships between the bolt load and the second and third order power spectral moment in a wide range of the bolt load. The character of the observed relationship was dependent on the transducer location. For sensors mounted on the first plate the decrease of the indicator with the increase of the bolt load was observed, while for sensors located on the second plate the increase of the indicator was connected with the increasing bolt load. The trends occurring for the second and the third modified power spectral moment can be used to formulate the index of joint condition.

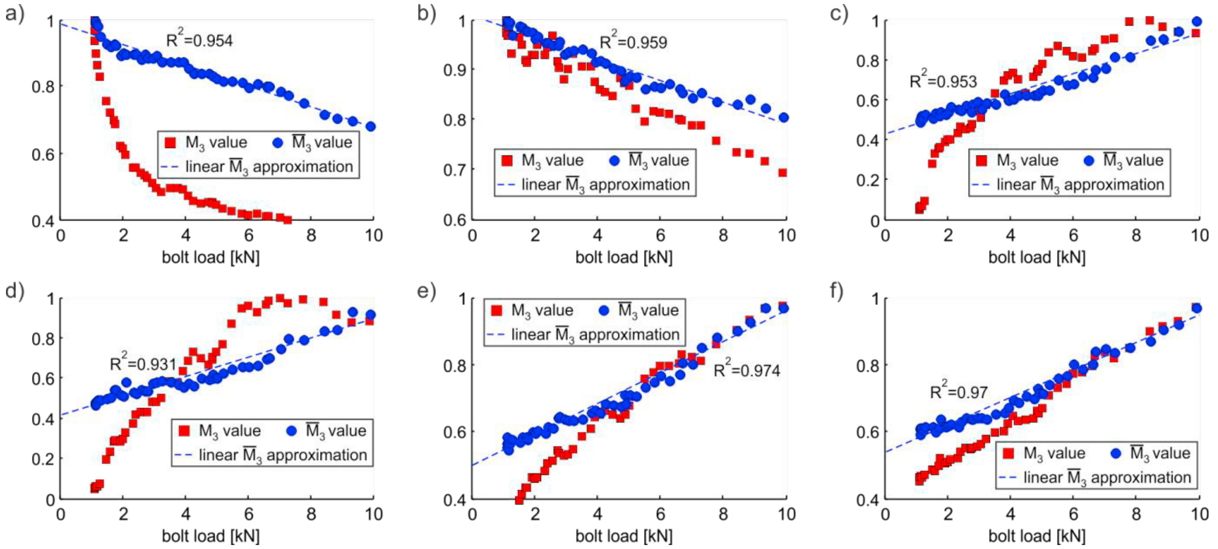

Fig. 7. The relationship between the bolt load and the third-order power spectral moment calculated for the signal registered by sensor: (a) S1; (b) S2; (c) S3; (d) S4; (e) S5; (f) S6.

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