Detection, Localisation, and Quantification of Bolt Looseness in an Aluminium Plate Using Lamb Wave Analysis

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ABSTRACT

In this paper a method is presented to detect and locate loose bolts. This method focuses on changes in Lamb waves when they encounter a different propagation path, whether that is in the form of stress concentrations, or the intensity of reflection from a change in contact area. Utilising this method, the authors show that a loose bolt can be located for a variety of different torque levels. However, the sensitivity to detecting the extent of the damage proved to show no benefits and further investigation is needed.

INTRODUCTION

Bolt connections are one of the most fundamental joining mechanisms used in engineering because of their ease of disassembly for maintenance and versatility. Bolted joints can fail because of varying mechanisms but the two most common causes of in-service failures of bolted joints occur from errors in the initial pre-load of the bolts, and from dynamic loosening of the pre-load [1]. Bolts can be loosened dynamically via a multitude of loading conditions, such as vibrations, shock loading and thermal loading. If the bolts have not been properly loaded or they have lost torque from $in-situ$ use, the damage can progress and result in chattering. Eventually, this chattering can be significant enough to cause the part to fail. The reduction in torque on one or more bolts can also decrease the fatigue life of the mechanical part [2]. In order to prevent this structural damage from occurring, it would be useful to have a reliable assessment method to determine the extent of bolt looseness in a structure that is susceptible to these forms of failure.

Several approaches aimed at detecting and quantifying bolt looseness exist in the literature, such as the electrical resistance probe method, electro-mechanical methods, and simply utilising a torque wrench to measure by hand [3–5]. All these methods prove to be labour intensive and induce a high cost. One method of structural health monitoring that has emerged as a powerful tool for damage detection is the utilisation of ultrasonic guided wave-based monitoring techniques; more specifically, the use of Lamb wave monitoring techniques [4, 6–9].

The literature shows a wide range of bolt looseness detection methods that utilise Lamb waves. Similarly to damage detection methods used in other fields of Lamb wave research, the forms of damage detection can be split into two main categories; linear

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guided waves and nonlinear guided waves. Linear methods utilise the linear parameters of guided waves such as wave amplitude, wave velocity and attenuation. Nonlinear methods make use of effects such as side bands and higher harmonics. A popular choice is to measure the amount of Lamb wave energy that passes over a lap joint [10–12]. Another similar method utilises the nonlinear effects of Lamb waves when they interact with surfaces that are in contact. If there is inadequate torque between the two surfaces the acoustic impedance will increase and result in a larger range of the appeared harmonic [8, 13]. While these methods prove to be successful, they only work when trying to determine the tightness of bolts across a lap joint; this may not be possible to achieve and could be complicated to implement in a more complex structure. Other linear and nonlinear detection methods have been researched such as; side band techniques [14,15], the velocity-ratio method [16] and nonlinear wave mixing [17].

Predominantly, these methods have focused on single bolt hole scenarios, if there is a large structure that requires the torque be determined for multiple bolts, this can be very time consuming and labour intensive. Focus on multi-bolted structures has been limited to research on satellites which possess very high complexity [18, 19]. These multi-bolt detection techniques take advantage of linear and nonlinear characteristics of Lamb waves; however, because of this high complexity, nonlinear analysis can become complex and difficult. One successful method of long-range bolt looseness detection is to determine the extent of the damage from the change in linear effects, such as velocity and wave amplitude, from increased stress concentrations. When torque is applied to a surface, a local stress concentration will appear around the bolt hole; increasing this torque will increase the stress concentration in that area. It is well documented that when Lamb waves interact with a stress field the propagation velocity will be changed and thus induce a phase shift [20]. Doyle $et\ al.$ [18] also showed that increasing the torque will result in a decrease in the amplitude of the recorded wave; this proved to be a successful method for detection of a fully loose bolt compared to the baseline of a bolt torqued to 50 Nm, with potential to localise the bolt. Following the success of this method the authors propose a method to locate and evaluate the extent of a bolt's looseness for a bolted plate which is smaller in size and with a smaller bolt to determine the sensitivity of this method, with future aims of applying this to a more complex structure containing multiple bolts.

DAMAGE DETECTION AND LOCALISATION METHODOLOGY

The paper being presented is preliminary work and, as such, only one bolt is currently used to analyse the sensitivity of a small bolt at relatively-low torque. In order to detect the change in torque linear features need to be extracted; these are the onset time of the damage, t_{damage}, and the peak amplitude of the wave at the damage, p_{damage}. It is necessary to determine a baseline to compare these features to. The baseline in this case is where the bolt is torqued up to its operational level; as this experiment used only an M5 bolt, the initial operational torque was 4.5 Nm. To determine the onset time of the damage it is necessary to observe where the signal deviations occur. When a Lamb wave interacts with damage or interacts with an area of increased stress it will induce a change in the attenuation in the wave. When inspecting the signal, it is not always clear where exactly this disturbance occurs as it will not usually manifest itself as a

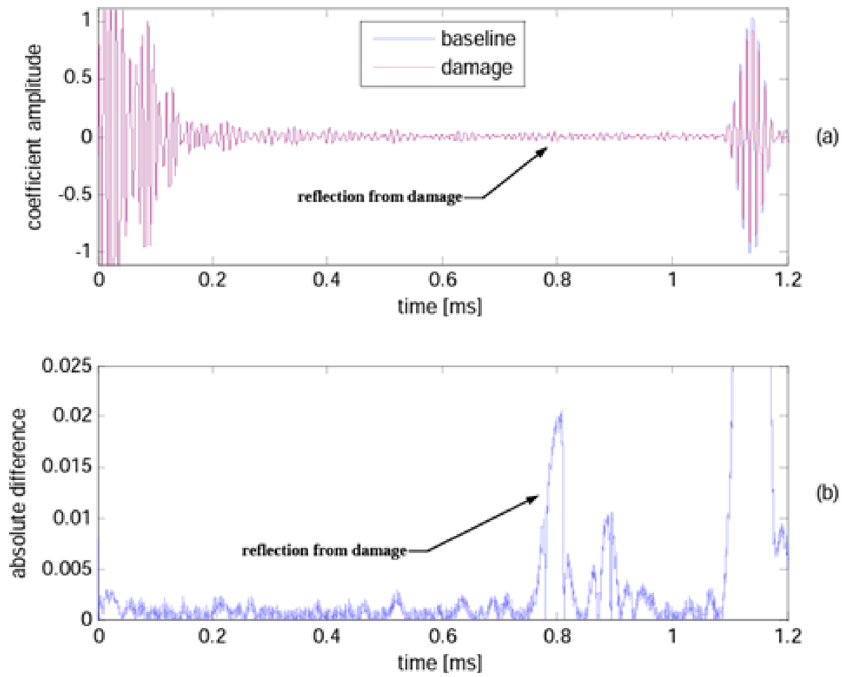


Figure 1. Measured response (top) and the baseline subtraction (bottom) used to determine the reflected Lamb waves, taken from Thien [22].

distinct peak present in the signal. To overcome this challenge, the baseline signal of a particular sensor-actuator pair can be subtracted from the recorded signal. If the signals are nominally similar, then the difference should result in auto-correlation of residual. If there is damage present, the baseline subtraction process should reveal the presence of the increased attenuation or impact of the reflected wave [21]. Figure 1 shows an example of the baseline subtraction method used for detecting damage in pipes [22]. As the deviations are small it is important to limit the sensitivity of the signal to noise and environmental variations. This can be achieved by applying a low-pass filter centred around the excitation frequency, and a Hilbert transform to envelope the signal. The exact location is found by determining the time of arrival of the first S0 mode, which is found using the Akaike information criterion [23]. This value is the subtracted from the time of the first peak; this difference in time of arrival corresponds to the bolt hole location.

The time of arrival of the damage signal to the sensor can now be used as a feature to determine the location of the damage. This can be achieved via the ellipse drawing method, where the time of arrival can be used to calculate the distance from the sensor to a defect. An example of a time ellipses can be seen in Figure 2.

The time associated with a propagating wave while passing through damage is denoted by,

$$t = \frac{d_1}{c_p} + \frac{d_2}{c_p} \tag{1}$$

where d_1 is the distance from the actuator to the damage, d_2 is the distance from the damage to the sensor and c_p is the phase velocity of the excited mode. As this is

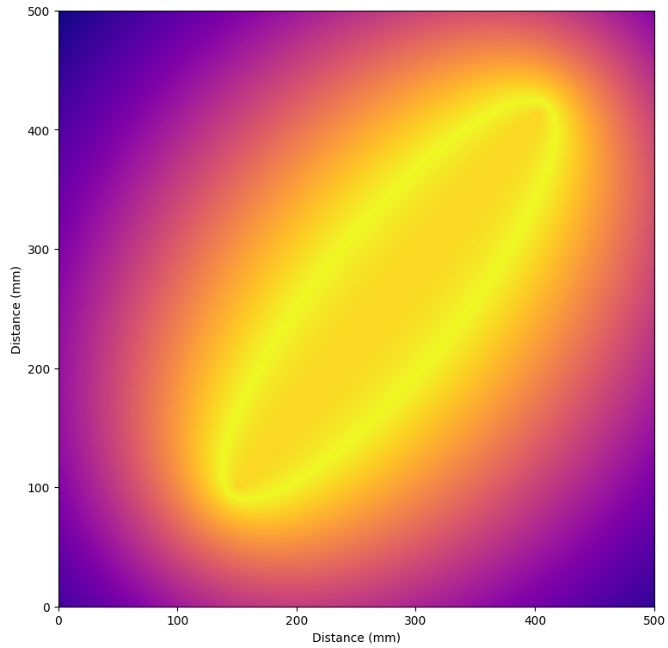


Figure 2. Example of a damage ellipses for one actuator-sensor pair given a specific time of arrival.

a simple isotropic plate, both phase velocities are assumed to be the same and are both taken for the S0 mode; although this may not be entirely the case as mode conversion can occur when Lamb waves interact with damage [20]. To construct an ellipse that can determine the location of the damage in the plate it is necessary to create a map of the damage interaction time of the entire plate and determining the time $t_i^{j,k}$ that it would take a wave to travel via point i on the plate from an actuator at position j to a sensor at position k.

$$t_i^{j,k} = \frac{\sqrt{(x_i - x_j)^2}}{c_p} + \frac{\sqrt{(x_i - x_k)^2}}{c_p} \tag{2}$$

In order to combine all the time maps for all actuator-sensor pairs, the time map is normalised with respect to the damage time, t_{damage}; this gives all ellipses a value from zero to one and prevents the longer ellipses with higher arrival times from dominating the combined damage maps.

$$E_i^{j,k} = t_i^{j,k} / t_{damage} \tag{3}$$

The final map is the product of all the actuator-sensor time maps.

$$D_i = \prod_n E_i^n \tag{4}$$

This approach can be used to find the estimate the extent of the looseness of the bolt. The larger the damage (i.e. how loose the bolt is) the more distinct the peak will be when compared to the baseline, and therefore the larger p_{damage} will be. The value of p_{damage} can be used to scale the damage map using,

	x Position (mm)	y Position (mm)
PZT 1	85	405
PZT 2	145	110
PZT 3	250	195
PZT 4	305	350
PZT 5	400	150

TABLE I. TABLE OF SENSOR/ACTUATOR LOCATIONS

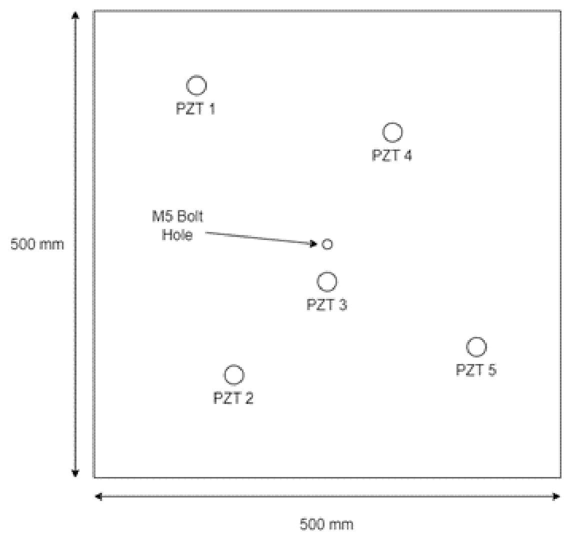


Figure 3. Diagram of experimental setup for data collection.

$$S_i = \prod_n p^n_{damage} E^n_i \tag{5}$$

EXPERIMENTAL SETUP

The proposed method was tested on a square plate of aluminium 6061. The specimen's dimensions, target bolt, and piezo-electric transducer (PZT) locations, which were used for actuating and sensing, are shown in Figure 3. The experimental study utilised a National Instruments PXIe-1082 with two multiplexers, an embedded controller, an arbitrary waveform generator (AWG) and an oscilloscope. The AWG had a sampling frequency of 20 MHz and the oscilloscope was set at a sampling frequency of 30 MHz. The oscilloscope was set to such a high sampling frequency becuase of the small scale of the plate; this ensures that no information on the damage location is lost. Only one actuator was used at any one time while the other four PZTs were acting as sensors. The PZTs were arranged to get a good coverage over the whole plate, while maintaining asymmetry of recordings. The sensor positions are given in Table I.

The excitation frequency was 100 kHz as this only excited the fundamental S0 and A0 modes but also kept a significant difference in phase velocities between them. The difference in velocities simplified the analysis, as it allowed for clearer separation be-

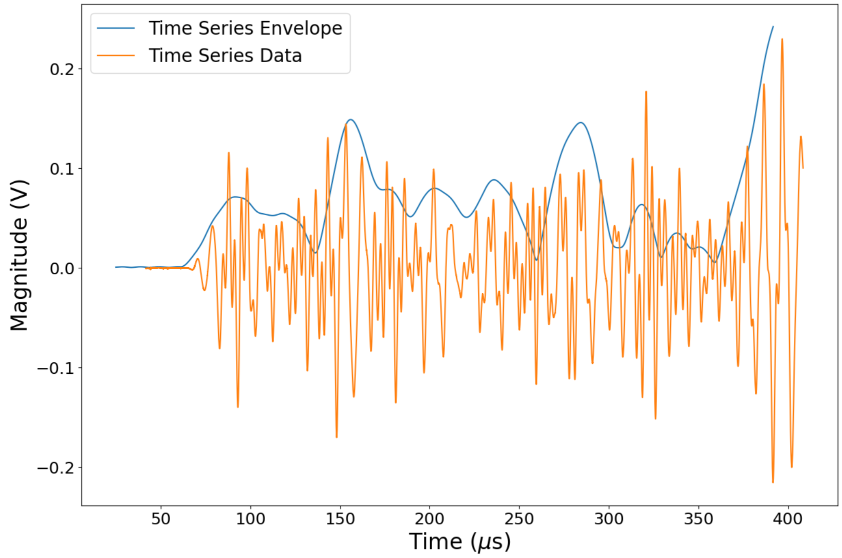


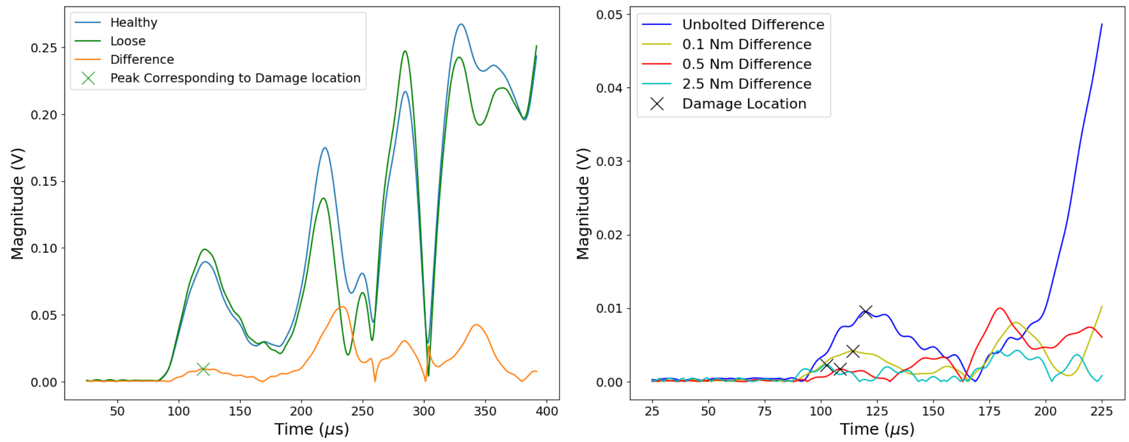
Figure 4. Recorded signal compared with post-processed signal.

tween the S0 and A0 modes; thus allowing for only the S0 mode to be considered. The baseline torque was 4.5 Nm. The bolt was subsequently completely taken out and then torqued to 0.1, 0.5 and 2.5 Nm as a preliminary test of sensitivity. Damage quantification and localisation was performed after all damage states were collected.

RESULTS AND DISCUSSION

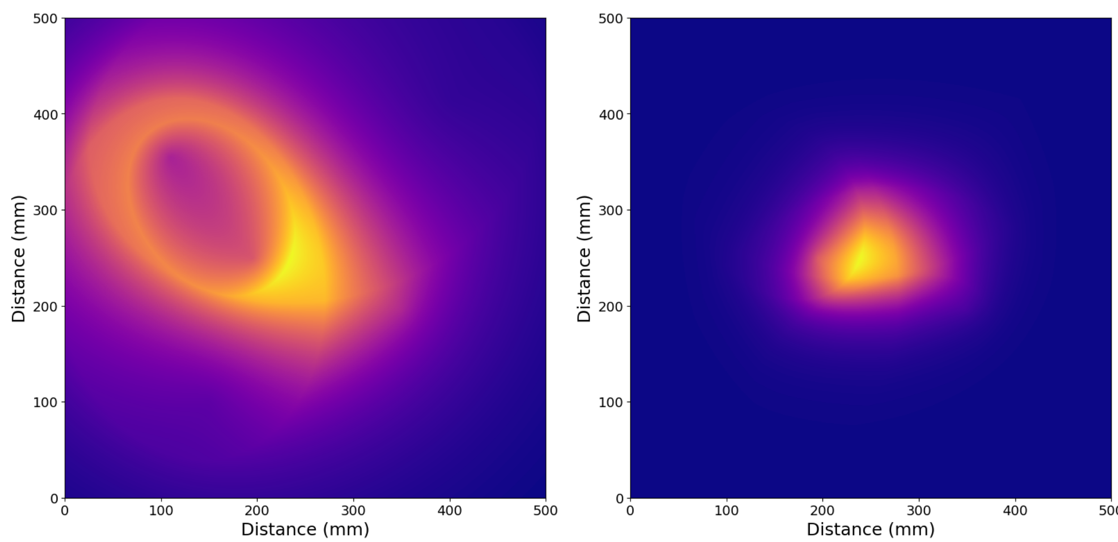
Figure 4 shows an example of the signal and the resultant post-processing used for feature extraction. Figure 5a shows the method of feature extraction highlighting where the time of arrival and the peak amplitude of the damage is. Figure 5b compares the amplitude and phase of the signal at the varying levels of torque. At low levels of torque, loose and at 0.1 Nm, there is a significant difference in the peak amplitude that corresponds with the damage. At higher levels of torque the peak height rapidly decreases, indicting that there may not be a significant difference at these levels. While the peak amplitude may not be very sensitive there is still quite a difference in the phase shift at these torques which may prove to be a more sensitive feature to analyse when attempting to determine the extent of the bolt looseness.

Using Eq.3 an ellipses map was created using a single actuator with four sensor pairs. An example of the result of these ellipses maps can be seen in Figure 6a. As can be seen, the location is not very specific and covers a broad area. Figure 6b shows what happens when one combines the data collected from more than one actuator, in this case four. The area in which the bolt could potentially be in drastically decreases, the prediction also gets much closer to the true location of the bolt; this can be seen in Table II. Increasing the data density would further increase the accuracy of this prediction. This method provides an accurate location but leaves room for uncertainty for the user's suggestion for what area to look in. One way to improve on this method would be to introduce mechanisms for assessing the uncertainty in the localisation [24], and using sparse data algorithms to get a more accurate prediction [25].



(a) (b)

Figure 5. (a) Comparison between the baseline healthy signal, the loose signal and the resultant baseline subtraction with the peak representing the damage location; (b) Comparison of peaks for all torques at damage location.



(a) (b)

Figure 6. (a) Time map for one actuator; (b) Damage map for all actuator-sensor pairs.

	x Position (mm)	y Position (mm)	Difference (mm)
Actual bolt position	250	250	——
Calculated loose bolt position	239	237	17.03
Calculated 0.1 Nm	234	241	18.36
Calculated 0.5 Nm	251	228	22.02
Calculated 2.5 Nm	252	238	12.17

TABLE II. TABLE COMPARING THE TRUE LOCATION TO THE PREDICTED LOCATION AND THE DIFFERENCE BETWEEN THE TWO

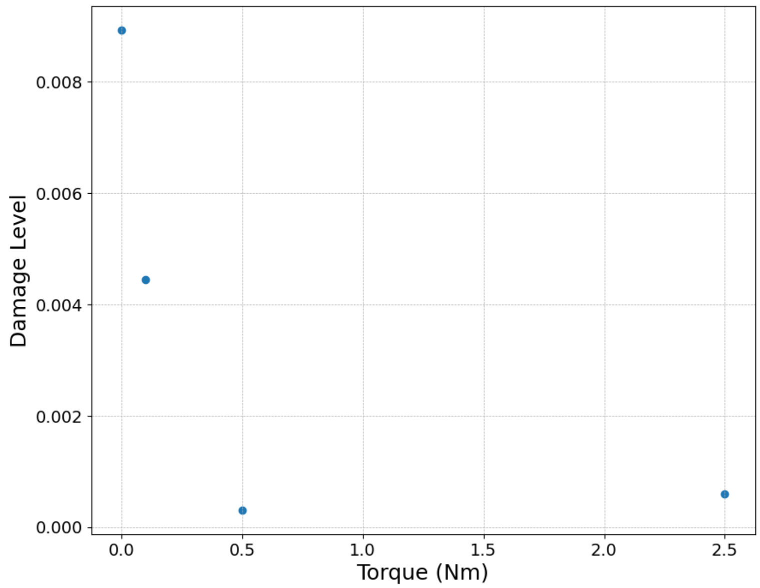


Figure 7. Calculated damage levels for varying levels of torque, which correlate to fastener torque

Figure 7 shows the result of the scaled damage approach to determine its sensitivity to quantifying the level of fastener torque. As Figure 7 shows, fastener torque is initially correlated to the torque of the bolt; however, as the torque became closer to the value of the baseline torque the difference becomes variable and does not indicate any specific trend. The 2.5 Nm estimated damage value is in fact higher than that of 0.5 Nm. This could be because at higher torque levels the difference in the amount of energy being reflected becomes insignificant. Although the extent cannot be determined from this method, there are features that could be used to determine this difference, such as the nonlinear aspects from the Lamb waves, as previously mentioned in the introduction. Further work will be conducted on the plate to test for the sensitivity of the nonlinear effects; such as the influence of side bands and higher harmonics, as well as investigating the capabilities of exciting two frequencies, and measuring the response, for detection and localisation of the loose bolt. Further analysis will also be completed to determine whether the data collected for the 2.5 Nm scenario was an anomaly.

CONCLUSION

In this paper, a Lamb wave-based method was used to detect, locate and quantify the looseness of a bolt in an aluminium plate. This method has shown to be able to successfully determine that there is loose bolt and to locate it to within 18 mm. While there was a clear decrease indication of the extent of the damage in the complete unbolted and 0.1 Nm torque levels, the damage extent becomes more obscure at higher levels of torque. However, there are other features that can be extracted to determine the fastener torque. Looking forward these features will be analysed to determine their sensitivity. Furthermore, this method will be applied to a plate with an array of bolts to determine its capability in localising a loose bolt in a more complex structure.

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