Bolt Looseness Detection under Changing Temperature Conditions
using Independent Component Analysis

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Abstract
Damage detection technology based on guided wave is used widely in structural health monitoring, which relies on comparing response signals with baseline records. However, the temperature variation can also produce large changes in guided wave signals, thereby causing a false alarm of damage detection. In this paper, independent component analysis (ICA) method was developed to process guided wave response signal for separating damage-induced information from coherent interference signal. As a result, the influence of temperature variation could be eliminated in the process of damage localization. In the laboratory, the experiment of bolt looseness damage detection was made in the environment of temperature variation. The collected signals were utilized in damage location estimation after processing by ICA. It showed good result for bolt looseness localization, which indicated that this method is robust to the temperature variation exhibited in damage detection based on guided wave.

Keywords: Bolt looseness, Damage detection, Guided wave, Temperature variation, Independent component analysis

1. INTRODUCTION
Bolted connection is one of the most widely used type of attachment in many engineering structures because of its convenience to use and high reliability. However, when bolted connection was acted by alternating loads or forced vibration, prestress relaxation and bolt looseness may occur, which will cause damage to the structural integrity and affect the normal operation of equipment. What’s worse, it’s difficult to observe bolted condition because bolted connection is almost inside of the structures. Therefore, it’s of significance to detect bolted situation and estimate the reliability of bolted connections.

In recent years, using damage prediction system in civil, mechanical, aerospace and other engineering structures has increasingly become a consensus [1]. A variety of damage detection techniques have been developed rapidly and widely used. In which, guided wave based damage detection technology has been identified as a class of potential technology for structure health monitoring (SHM) of large areas. By pasting sensors at specified location, it’s valid for bolted situation detection using this
technology. Wang et al. used the time reversal method based on guided wave to study the change of bolt preload, and the state of bolt was successfully judged [2]. Based on the probability analysis of wavelet coefficients, Park et al. identified bolt looseness successfully [3]. Jhang et al. studied on single bolt under axial stress by measuring time of flight (TOF) [4].

The key of guided wave detection method is to recognize damage-induced change in guided wave signals. But when the material properties of the structure are changed because of changes in the surrounding environment, the propagation of guided wave will be affected, which causing a false alarm of damage detection. Therefore, it is necessary to eliminate the effects of interference factors, especially environmental temperature change, in the process of guided wave propagation or the response signals processing. A. J. Croxford et al. studied on the effect of a temperature compensation technique by applying an analytical model to different wave modalities and sensor geometries [5]. T. Clarke et al. developed a temperature compensation strategy of combining the optimal baseline selection (OBS) and the baseline signal stretch (BSS) methods to reduce the number of signals which was large because of environmental effects [6]. Although these methods have achieved remarkable achievements in eliminating the effects of temperature change, very few work has been reported about focusing on the processing of signals statistical data obtained in changing temperature conditions. In this paper, the ICA method is utilized to exclude the influence of the temperature on the Lamb wave detection in the bolt loosening. In the laboratory, by changing the temperature of aluminum plate, the experiment of bolt looseness damage detection was made. The collected signals were used in damage location detection after processing by ICA.

2. THEORY

2.1 Influence of temperature on wave propagation

The influence of temperature change on guided wave propagation is represented in changing the material properties of the structure, the sensors, and the adhesive layer. It is possible through careful selection of adhesives and transducers to minimize the variability from the bonds; however, the changes in the material properties of the structure cannot be altered [5]. For demonstrating the influence of temperature on wave propagation, one Hanning-windowed tone bursts are considered, \( I_0 \), which represent the baseline signal. It can be defined as

\[
I_0 = u_0 h(t) \sin \omega t
\]

(1)

where \( h(t) \) is the Hanning-window function, \( u_0 \) is the amplitude, \( \omega \) and \( t \) are angular frequency and time respectively. The current signal, \( I_1 \), affected by temperature change will be added a time shift, \( \delta t \), compared to \( I_0 \). Hence,

\[
I_1 = u_0 h(t) \sin \omega(t + \delta t)
\]

(2)

Note that the change in temperature causes a translation of the received signal in time. It is necessary to relate \( \delta t \) to the variation in temperature, \( \delta T \). Starting from
\[ t = \frac{d}{v} \] and partially differentiating with respect to both \( d \) and \( v \) gives

\[ \frac{\delta t}{\delta t} = \frac{1}{v} \frac{\delta d}{\delta t} - \frac{d}{v^2} \frac{\delta v}{\delta t} \]  

(3)

where \( d \) is the propagation distance, \( v \) is the propagation velocity. There are following relations between temperature and the propagation distance:

\[ \frac{\delta d}{\delta T} = \alpha d \]  

(4)

where \( \alpha \) is the coefficient of thermal expansion. And the relation between temperature and the propagation velocity can be represented as

\[ \frac{\delta v}{\delta T} = k \]  

(5)

where \( k \) is the coefficient of change in velocity with temperature. Combining Eqs. (4) and (5) with Eq. (3) gives

\[ \delta t = \frac{d}{v} \left( \alpha - \frac{k}{v} \right) \delta T \]  

(6)

Note that the size of \( k/v \) is typically one to two orders of magnitude larger than \( \alpha \), so increases in temperature will always cause a positive \( \delta t \). Subtract \( I_1 \) from \( I_0 \), and define \( U_0 = u_0 h(t) \)

\[ I_1 - I_0 = U_0 (\sin \omega (t + \delta t) - \sin \omega t) \]  

(7)

Assuming that \( \delta t \) is small enough, there are following results:

\[ |I_1 - I_0|_{max} = 2\pi f U_0 \delta T \]  

(8)

where \( f \) is the frequency. By combining Eqs. (6) and (8), and considering \( \lambda = v/f \) gives

\[ |I_1 - I_0|_{max} = 2\pi \frac{d}{\lambda} U_0 \beta \delta T \]  

(9)

where \( \beta = \left( \alpha - \frac{k}{v} \right) \). Eq. (9) shows that the level of subtracted signal is proportional to the temperature variation when the propagation distance and the wavelength are constant.

### 2.2 ICA methodology

In this paper, the ICA method is utilized to exclude the influence of the temperature on the Lamb wave propagation. ICA theory was first proposed by Herault J and Jutten C in 1980s, and its essence is a kind of optimization algorithm based on blind source separation. The intension of ICA technique is that after applying the algorithm, a set of multidimensional data will be transformed into components that are as statistically independent as possible [7]. Numerous implementations of ICA are available, but the FastICA algorithm is used in this study because of its great calculation speed. A brief overview of the Fast ICA method is as follows.
First, combine the collected guided wave signals $x_1(t), x_2(t), \ldots, x_n(t)$ into a matrix $X$. For reducing the complexity of matrix $X$, we choose the whitening processing. Whitening process means that transform matrix $X$ to make its elements uncorrelated and it meet the following equation.

$$E[W, W^T] = I$$  \hspace{1cm} (10)

where $W$ is whitening matrix of matrix $X$; $E[W, W^T]$ denotes the covariance matrix of matrix $W$; $I$ is the unit matrix. A simple whitening method is to use the eigenvalue decomposition of the matrix $X$. The equation is as follows.

$$W = D^{-1/2}V^T$$  \hspace{1cm} (11)

where $D$ and $V$ are the eigenvalue matrix and the eigenvector matrix of the covariance matrix of $X$, respectively; superscript “$-1/2$” represents the reciprocal of square root operation. $[\cdot]^T$ represents the transposing operation. Then, the iterative calculation is used to optimize the computation for each column of $W$. If $W$ is chosen as the initial value of optimization, K-order iteration results $W_{n,k}$, obtaining by k iterations through Newton formula-simplified FastICA algorithm, can be expressed as

$$W_{n,k} = (Zg(W_{n,k-1}^TZ)) - (g'(W_{n,k-1}^TZ))W_{n,k-1}$$  \hspace{1cm} (12)

where $Z = WX$ is an orthogonal matrix; $g(x)$ is a nonlinear function using the $x$ as the variable; $\langle \cdot \rangle$ represents the averaging operation; superscript “$-$” represents the normalized processing.

Following, select function $g(x)$ and perform the iteration optimization for each column of $W$ by using Eq. (6) until the iteration result satisfies the convergence condition

$$\left\{ \left| W_{n,k} \right| - \left| W_{n,k-1} \right| \right\} < \epsilon$$  \hspace{1cm} (13)

where $\{\cdot\}$ denotes the summation operation; $|\cdot|$ denotes absolute value operation; $\epsilon$ is the convergence threshold. When the iteration is performed for all columns of $W$, we can obtain the optimization matrix $A$ and $S$.

The signals that are the rows of $S$ will be the new representation we want in which the original signal and the coherent noise caused by temperature vibration have been separated into different components. By merely selecting the row that is most similar to the baseline signal, the time shift, $\delta t$, caused by temperature vibration can be excluded, which means that the influence of temperature variation on wave propagation can be eliminated.

3. EXPERIMENT

3.1 Experimental setup and procedure

The experimental setup is shown in Figure 1, which is combined with NI data acquisition system and experimental aluminum plate. The experimental aluminum plate is 1000 mm by 1000 mm by 2 mm with two arrays of PZT actuators/sensors.
bonded on the plate surface. The aluminum plate is connected with aluminum stiffener through four bolts (#1-#4). There are two thermocouples sticking on aluminum plate for measuring the temperature. The specific location of piezoelectric arrays and bolts on the experimental aluminum plate is shown in Figure 2. To simulate free boundary condition, the aluminum plate is placed on a soft sponge. An infrared heating lamp (shown in Figure 1b) beneath the aluminum plate is used to create temperature variation condition.

NI data acquisition system is responsible for exciting PZT actuator and collecting the sensing signal. In this experiment, a PXIe-6124 data acquisition card is selected to send the excitation signal and collect the sensing signal. And the collected signal data will be dealt by data analysis program based on LabVIEW.

In order to reduce the complexity of the experiment, only 8 piezoelectric plates (#1-#8 in Figure 2) were taken to carry out the excitation and reception of the guided waves. PZT #1-#4 are actuators, PZT #5-#8 are sensors. During the experiment, a 2-Vpp, 125-KHz, and 3.5-cycle sinusoidal signal within a Hanning window was used as the excitation, as illustrated in figure 3. Firstly, under room temperature condition (22°C), an excitation signal was applied to actuators #1 to #4 sequentially when the four bolts were in full tight state. The other four sensors #5 to #8 recorded the signals simultaneously. The recorded signals were treated as the reference signal. Then, turned on the infrared lamp to heat the aluminum plate, the procedure of excitation and reception was repeated when the temperature of aluminum plate reached 27.5°C, 32°C, 37.5°C, 42°C successively. Finally, adjust bolt #2 to loose state, and collected the damaged signals.
3.2 Experimental results and discussion

3.2.1 Influence of temperature on Lamb wave signal

Figure 4 shows the comparisons between the signals obtained at the temperature of 22.0°C and 27.5°C for the sensing path #1 to #6. It is the zoomed-in portion on A0 mode of the signal. It can be observed that there is phase shift between the signals at the temperatures of 22.5°C and 27.5°C, and the phase of signal at the temperature of 27.5°C is lag behind that at the temperature of 22.0°C. This is consistent with the theory of the influence of temperature on the guided wave signal in Section 2.1—a positive temperature difference leads to a positive time shift in the guided wave.

In order to further verify the theory of the influence of the temperature on the guided wave, comparisons in time domain between the signals at five different temperatures were made, which are shown in Figure 5. It can be observed that the signal at the temperature of 22.0°C takes the place in front, which followed by the
signals at the temperatures of 27.5°C, 32.0°C, 37.5°C, and the signal at the temperature of 42.0°C is lagging behind. It means that, the time shift between Lamb wave signals is gradually increased with the increase of temperature, which is consistent with the positive correlation between \( \delta t \) and \( \delta T \) in Eq. (6).

![Graph showing signal comparisons at different temperatures](image)

Figure 5: Comparisons between the signals obtained at different temperatures (Path # 1 to # 6).

It’s easily understood that when the temperature variation reaches to a certain value, the damage detection based on Lamb wave will cause a false alarm because of the influence of temperature variation. For studying this phenomenon, the damage detection algorithm was calculated by taken the signals at the temperatures of 22.0°C and 27.5°C as the reference signal and the current signal respectively. In this experiment, correlation coefficient localization algorithm was utilized for damage detection and localization, which was realized by considering the correlation coefficients of every sensing path as damage index. The result of damage detection is shown in Figure 6. It can be noticed that there is a bright pixel area representing the damage in the figure. This result is obtained in the original state without damage when four bolts are in full tight state, which indicates that the temperature difference of 5.5°C is sufficient to cause a false alarm of damage detection on aluminum plate.

![Damage detection estimation and result](image)

Figure 6: Damage detection estimation without ICA processing under different temperature condition.
3.2.2 Results of applying ICA

By taken the signals at different temperatures as input signals, ICA algorithm was calculated. Among the output signals, the original signals were found by comparing the output signals with baseline signal. The output signal obtained from the sensing path # 1 to # 6 was shown in Figure 7. It is apparent that, compared to the signal at 27.5°C, the signal processed by ICA is more coincident with the signal at 22°C. It shows that the ICA algorithm can remove the influence of the temperature change to an extent, so that the output is well close to the baseline signal (signal at 22°C).

![Figure 7: Comparisons between the signals at different temperatures and the original input signal from ICA (Path # 1 to # 6).](image_url)

In this experiment, the subtracted signals relative to the amplitude of the baseline signal were analyzed. The result about the subtracted signal obtained when signal at 22.0°C subtracts signal at 27.5°C is shown in Figure 8 and correspond to a worst case of -14.83 dB. While the amplitude of the subtracted signal when signal at 22.0°C subtracts output signal from ICA is -18.86 dB, which shown in Figure 9. It demonstrated that the difference between the signal at 22.0°C and the output signal from ICA algorithm is overall smaller than that when signal at 22.0°C subtracts signal at 27.5 °C. It also proves that the signal processed by ICA is close to the signal at 22.0 °C.

![Figure 8: Amplitude of the subtracted signal obtained when signal at 22.0°C subtract signal at 27.5°C](image_url)
Finally, the original signals obtained from ICA algorithm were applied to damage location estimation. The result of correlation coefficient localization algorithm is shown in Figure 10(a). Figure 10(b) represents the result with the threshold value 0.96 taken. It is apparent that the possible damage location got from correlation coefficient localization algorithm covers the actual damage location. It shows that looseness of bolt #2 has been successfully located, which suggested that the experimental results verify the effectiveness of ICA method in eliminating temperature effect on guided wave propagation.

![Figure 9: Amplitude of the subtracted signal obtained when signal at 22°C subtract output signal from ICA](image)

4. CONCLUSIONS

In this paper, we have discussed the feasibility of using ICA method in eliminating temperature effect on guided wave propagation. Through a combination of theoretical derivation and experimental results, we find that increasing temperature change leads to a gradual increasing time shift in the guided wave. When the temperature change reaches to a certain value, it will even produce a false alarm in the damage detection. One of the output signals is more coincident with the baseline signal (signal at 22.0°C), which is revealed in that the amplitude of the subtracted signal when signal at 22.0°C subtracts output signal from ICA is less than that when
signal at 22.0°C subtracts signal at 27.5 °C. Furthermore, it shows a good result of damage detection estimation when the output signals from ICA are used as the input data of location algorithm on the case that bolt #2 loose. All of these appear that ICA is a promising method for the processing of guided wave data collected in changing temperature conditions.

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REFERENCES


