ADALINE Network-Based Temperature Compensation Method for SHM Method

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ADALINE NETWORK-BASED TEMPERATURE COMPENSATION METHOD FOR SHM METHOD

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ABSTRACT

The performance of current PZTs array and Lamb wave based SHM methods is restricted by the temperature variation. As temperature has a significant influence on Lamb wave propagation which leading to false monitoring result even if the structure is under health status. A new temperature compensation method based on adaptive filter adaptive liner neural (ADALINE) network has been developed to compensate for the amplitude-change and phase-shift of Lamb wave due to temperature change. Network construction and procedure of compensation are discussed. The advantages of this proposed method are (1) Simple to be applied, (2) only a few baselines are required for a large temperature range. Experiments are conducted on a stiffened carbon fiber composite panel to verify the temperature compensation method under temperature range from -40°C to 80°C. Results show the presented method is effective. Damage image combined with this compensation method can detect the damage under temperature variations.

KEYWORDS : *structural health monitoring, Lamb wave, temperature compeasation, ADALINE network, damage image.*

INTRODUCTION

Much attention has been paid to piezoelectric transducers (PZTs) array and Lamb wave based structural health monitoring (SHM) method, because this method is sensitive to small damages of composite structures, and can achieve regional monitoring of large-scale structures [1]. Currently, baseline related method has shown to be one of the prominent option [2]. However, this method depends on the baseline signals acquired at the health status of the structure. The status of the structure can be determined by comparing baseline signal and monitoring signal with some SHM algorithms [3]. Such a process can be implemented well in the laboratory for steady environmental and operational conditions (EOC). But in practical applications, the monitoring signal is often affected by the changing EOC, which will lead to false monitoring results [4].

Temperature has shown to be one of the most influential EOC to Lamb wave signals [5]. Both theoretical and experimental researches have shown that Lamb wave propagation can be influenced by temperature, as the temperature can affect the piezoelectric properties, the condition of the structure, the adhesive layer between PZT and structure and Lamb wave propagation [6]. Over the last several years, a variety of methods for overcoming the temperature effect of Lamb wave acquired by PZTs have been proposed [7-11].

Many reference-free approach has been proposed [7, 8]. They want to fulfill damage estimation directly by using Lamb wave monitoring signals which are independent on Lamb wave baseline signals. The basic idea of these methods is that the damage induced signals can be extracted through Lamb wave monitoring signals by using special sensors placement, advanced signal processing methods or Lamb wave modes modulation mechanisms. These methods are hard to be applied on real aircraft structures at current stage as the direct wave, boundary reflections and muti-modes of Lamb wave signals are often mixed .

Temperature compensation method based on optimal baseline subtraction (OBS) and baseline signal stretch (BSS) has been studied by many researchers [9, 10]. In OBS method, a baseline dataset must be obtained under health status at an average temperature difference of 0.1°C [9]. In BSS method, the baseline signal is stretched or compressed by a stretch factor to match the monitoring signal [10]. The phase of Lamb wave signal has been well compensated in this method, while the amplitude of the signal is also temperature sensitive according to many researchers [5]. The combination of BSS and OBS can achieve a promising compensation accuracy, but this method still requires many baseline signals, namely the temperature difference between baseline dataset is optimized to 2°C [10]. A scale transform signal processing method is applied to improve the computational speed of BSS method [11].

Temperature compensation method based on numerical modeling is also studied by many researchers [12]. They try to construct a comprehensive Lamb wave propagation model to predict the full pitch-catch Lamb wave signals under changing temperature. Numerical versus experimental studies demonstrate that the high accuracy of temperature compensation of Lamb waves signals can be obtained on metallic structures. But with the application of composite structures, the accurate physical model is difficult to be acquired.

Recently, a physics-based temperature compensation model combined with matching pursuit signal analysis has been introduced [13]. Performance of this model is found to be at par with the OBS+BSS compensation method. A cointegration approach [14], which has been widely used in econometrics, has been proposed to remove the undesired temperature effect from Lamb wave data. This method is partially built on the analysis of the non-stationary behaviour of Lamb wave signal acquired at different stage. The procedure and computation of this method are of high complexity.

This paper proposes a temperature compensation method based on adaptive liner neural (ADALINE) network to compensate for the amplitude-change and phase-shift due to temperature. The advantages of the proposed method are as following : (1) Simple to be applied. After training, the network requires only 2 weights implement compensation in each temperature. (2) Small amount of baseline signals. Only 6 baseline signals are required in the temperature range from from -40°C to 80°C. (3) High accuracy on a stiffened carbon fiber composite panel. Experimental results shows that error is reduced from -12dB (amplitude error : 0.3V) to -25dB (amplitude error : 0.07V) after compensation.

1 EXPERIMENTAL RESEARCH ON TEMPERATURE INFLUENCE

1.1 Experimental setting

In this paper, a stiffened carbon fiber composite panel of thickness 2mm is adopted to study the temperature influence and the compensation method as shown in Figure 1. PZTs (thickness 0.5mm, diameter 8mm, PIC255, PI L.P.) are mounted to the surface of the composite panel by the epoxy adhesive 353ND (Epoxy Technology, Inc). The thickness of the adhesive layer is 0.08mm approximately. 20 actuator-sensor channels are defined.

An environmental chamber Challenge 250 (Angelantoni Industrie SpA, Fluctuation : ± 0.3°C) is adopted to simulate the temperature environment of PZTs. An integrated structural health monitoring system (ISS) [15] is adopted to fulfill the signal generating, frequency sweeping, multi-channel scanning and Lamb wave signals acquiring of the 20 actuator-sensor channels constructed by the PZT sensors. In order to study the temperature influence of Lamb wave signals, a five cycle sine burst is used as an excitation signal with a central frequency of 50kHz. The sampling rate is 10MHz.

The specimen is put into the chamber for a temperature pre-cycling to adapt the temperature range -40°C to 80°C. Then the chamber is programed to control its inner temperature from -40°C to 80°C and from 80°C to -40°C with a step of 2°C. At each step, temperature is hold for 2 minutes and the Lamb wave signals are acquired during this stable temperature stage. Temperature cycling under health status is repeated for three times. After that, A 100g mass is bonded in the center of the area surrounded by PZT 5, 6, 8 and 9 to simulate damage. Lamb wave signals are acquired at every 2 °C in the same way.

Through this experiment, Lamb wave signals under health and damage status at different temperatures are acquired. The signals acquired in this experiment are also used to validate the compensation method in damage image.

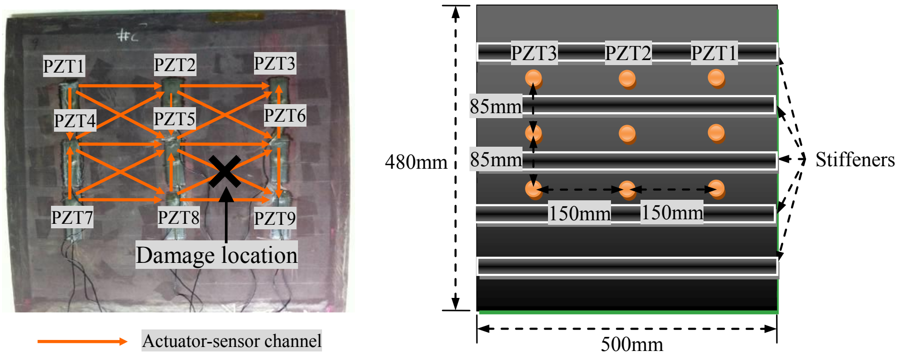


Figure 1: Composite panel and PZTs placement

1.2 Temperature influences on Lamb wave signals

In order to extract features of temperature influence on Lamb wave signals, time of arrival (TOA) and signal amplitude are characterized. Take actuator-sensor channel PZT1-PZT2 as an example, signals with frequency 50kHz at different temperatures in the range of -40°C to 80°C are illustrated in Figure 2 a). The TOA and amplitudes of the wave peaks in the first wave packets of signals at different temperatures are shown in Figure 2 b) and 2 c), respectively. It can be seen that the TOA of all wave peaks have a good linear relationship versus temperature, while the changes in amplitude are more complicated and nonlinear even in the same wave packet.

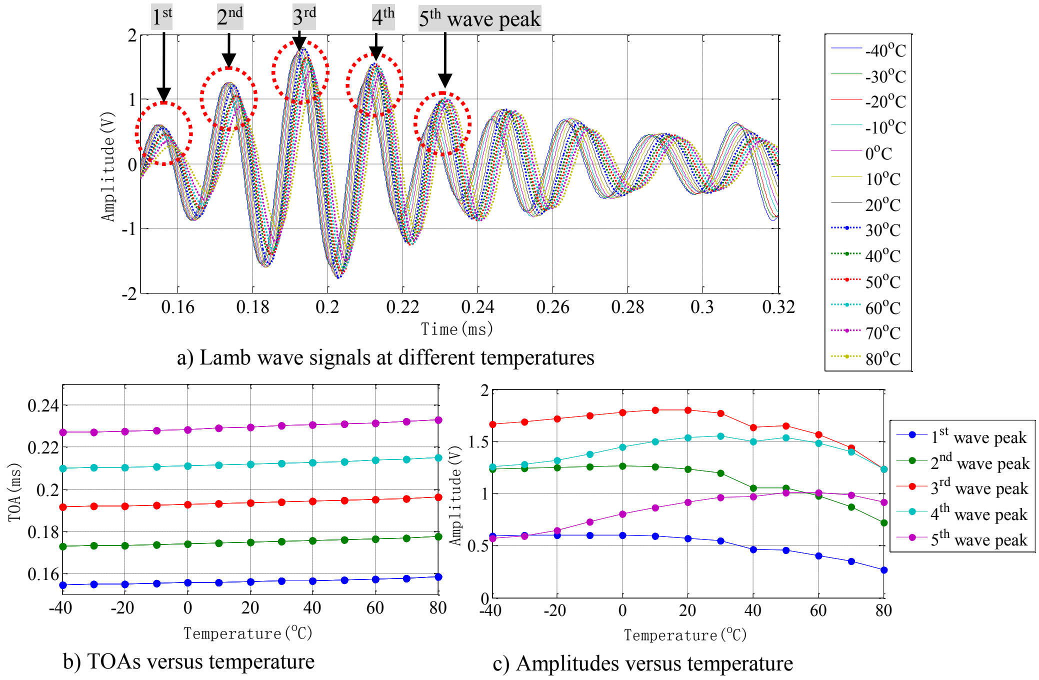


Figure 2: Temperature influence of Lamb wave signals

Considering the linear relationship versus temperature of TOA and the nonlinear of amplitude, two parameters called as phase changing rate (*PCR*, unit rad/°C) and maximum amplitude variation (*MAV*, unit %) are defined to quantify the temperature influence, respectively.

$$PCR = \frac{\left(TOA_{80°C} - TOA_{-40°C}\right) f_c}{120°C} \tag{1}$$

$$MAV = \frac{\left(Amplitude_{\max} - Amplitude_{\min}\right)}{Amplitude_{20°C}} \times 100\% \tag{2}$$

where f_c is the central frequency of Lamb wave signals.

Table 1 lists the two parameters of Lamb wave signals of each wave peak. It shows that *PCR* increase with wave peak growth, namely TOA is more sensitive to temperature when Lamb wave propagate longer in the structure. While *MAV* of each wave peak demonstrate different sensitivity under temperature variations.

Table 1: PCR and MAV of Lamb wave signals of each wave peak

Wave peak	*PCR*(10^{-3}rad/°C)	*MAV*(%)
1	1.625	58.54
2	1.917	43.99
3	1.958	31.53
4	2.042	20.56
5	2.500	47.88

2 TEMPERATURE COMPENSATION METHOD

2.1 The general idea of the method

As the results shown in section 1, temperature change will lead to an approximately linear delay to the TOA and nonlinear variation to amplitude. The artificial neural network (ANN) is often used to solve system nonlinear problems. Among the existing ANN, the adaptive filter ADALINE network can attenuate the amplitude and shift the phase of a signal by a weighted delay.

The procedure of proposed temperature compensation method is as follows :

(1) Database acquiring

Through the experiment conducted in section 1, Lamb wave signals are acquired from -40°C to 80°C with an interval of 2°C.

(2) Network training and storing

The whole temperature range is divided into 6 sub temperature scopes according to compensation standard which will be elaborated in the following section.

In each temperature scope, the central temperature is set to be reference temperature T_R and the Lamb wave signal S_R at this temperature is set to be the baseline signal. S_R is considered to be input of adaptive filter ADALINE network and the targets are Lamb wave signals S_1, S_2,…, S_i acquired at temperature T_1, T_2, … , T_i.

After training, a set of adaptive filter ADALINE networks with weights $\mathbf{w}_1$, $\mathbf{w}_2$,…, $\mathbf{w}_i$ are acquired for every temperature in this temperature scope. The network architecture for each temperature is the same, while the weights of the network are altered according to the monitoring temperature.

It should be emphasized that only one baseline signal and a set of weights of adaptive filter ADALINE network are needed to store in each temperature scope.

(3) Network application

In damage monitoring, the environmental temperature and the Lamb wave signal at this temperature are acquired. According to the environmental temperature, the weights of the adaptive filter ADALINE network and the baseline signal are determined. Finally, the reference baseline signal of the temperature scope is set to be the input to the adaptive filter ADALINE network and the output is the compensated baseline signal at the environmental temperature.

Once a set of weights are obtained and their performance indexes meet the compensation standard, they can be adopted in adaptive filter ADALINE network to temperature compensation.

2.2 The architecture of Adaptive filter ADALINE network

The architecture of the adaptive filter ADALINE network which contains two layers referred as inputs and ADALINE are shown in Figure 3. The layer of inputs is consisted of a tapped-delay-line (TDL). The input signal *f*(*t*) enters from the left. At the output of the TDL, there is a *M*-dimensional vector, consisting of the input signal at the current time and the signals which are tapped delayed from 0 to *M*-1 time steps. *M* denotes the order of the TDL. The output of the network can be presented as:

$$a(t) = \sum_{m=1}^{M} w_m f(t-m+1) \tag{5}$$

In the matrix from:

$$a = \mathbf{w}^T \mathbf{z} \tag{6}$$

where $\mathbf{w} = \begin{bmatrix} w_1 & w_2 & \cdots & w_M \end{bmatrix}^T$, $\mathbf{z} = \begin{bmatrix} f(t) & f(t-1) & \cdots & f(t-M+1) \end{bmatrix}^T$.

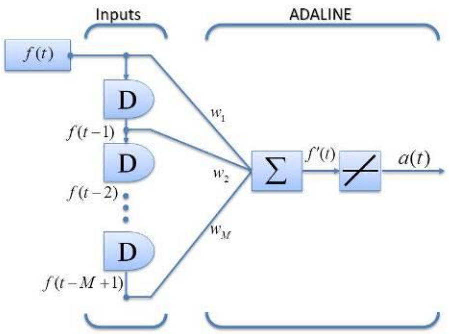


Figure 3: Network architecture of adaptive filter ADALINE

ADALINE network is shown in Figure 3. It has the same basic structure as the perceptron network (one layer). The only difference is that it has a linear transfer.

In this paper, adaptive filter ADALINE network with 2 order tapped delay line (M=2) is selected to fulfill the temperature compensation task. In that case, a neuron with two weights and no bias is sufficient to implement the filter. Such a filter with 2 order tapped delay line can amplitude-change and phase-shift Lamb wave signal in the desired way. According to our research, M is recommended set to be 2 for Lamb wave signal. Because ADALINE network with 2 orders tapped delay line is simple and easy to train. In addition, when M is set to be 3 or more than 3, the training results are not getting better and the weights become nonlinear to temperature.

The baseline signal *f*(*t*) acquired at T_1°C is the input of ADALINE network, while the output is *a*(*t*). The target of the network is the baseline signal $f_T(t)$ acquired at T_2°C. The goal of network training is to minimize the performance index, which is mean square error (MSE) in this paper, of the target $f_T(t)$ and the output *a*(*t*). In the training algorithm, the weights are updated with the least mean square (LMS) algorithm [16].

2.3 Compensation standard and temperature scope determination

In SHM applications, damage can be determined by evaluating maximum error of the subtracted signal between monitoring signal and baseline signal. In that case, a normalized maximum error *E*r is used to be the compensation standard and to validate the compensation results as shown in Equation (7).

$$E\text{r}=20\log\left(\max\left(\left|a(t)-f_T(t)\right|\right)/\max\left(\left|f_T(t)\right|\right)\right) \tag{7}$$

Where *a*(*t*) is the output of the network, $f_T(t)$ is the target Lamb wave signal.

According to the Lamb wave signals acquired in health and damage status in section 1, the maximum errors of their subtracted signals are -5.25dB (PZT5-PZT9, damage occurring in this path) and -29.78dB (PZT1-PZT2, no damage occurring in this path). Combining the results from the research [5, 6], Temperature compensation standard is set as *E*r<-25dB.

In this case, the temperature scope is set to be 20°C. The whole temperature range from -40°C to 80°C is divided into 6 sub temperature scopes. Lamb wave signals of 6 reference temperatures (-30°C, -10°C, 10°C, 30°C, 50°C, 70°C) are stored in the baseline signal database.

3 VALIDATION OF COMPENSATION METHOD

3.1 Signal compensation

By examining the compensated baselines signal with the baseline signal acquired at real condition, the result of the compensated effect can be obtained. For example, the environment temperature is at 20°C. In that case, the fourth temperature scope is selected and the reference temperature is 30°C. Thus, reference baseline signal at 30°C, which can compensate signals within the range of 20°C ~ 40°C, is selected as the input of the network. Meanwhile, the network weights for 20°C are selected from the weights database.

After applying the network, the output of the network is the compensated signal at 20°C, as shown in Figure 4. The figure illustrates that the amplitude of subtracted signal between reference signal (20°C) and target signal (30°C) is up to 0.2V. After compensation, the amplitude of subtracted signal between reference signal and compensated signal is less than 0.07V (normalized maximum error is -28dB) which meets the compensation standard.

For compensating the signal at other temperatures, the same algorithm and procedure can be applied. The compensation results are verified at each temperature as illustrated in Figure 5. In stiffened composite panel, temperature compensation scope of baseline signal is set to be 20°C. After compensation, the normalized maximum errors are less than -25dB at each temperature.

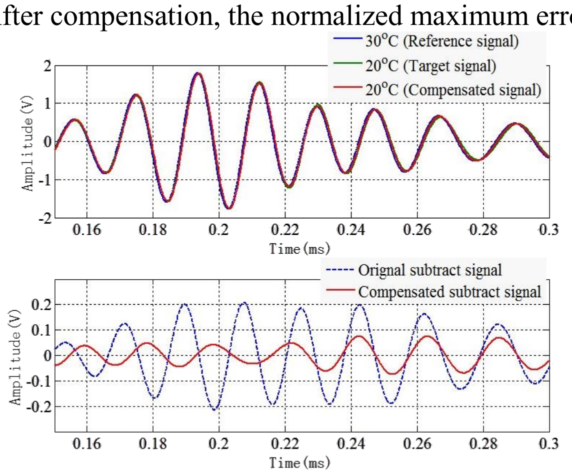


Figure 4 :Signal compensation from 30°C to 20°C

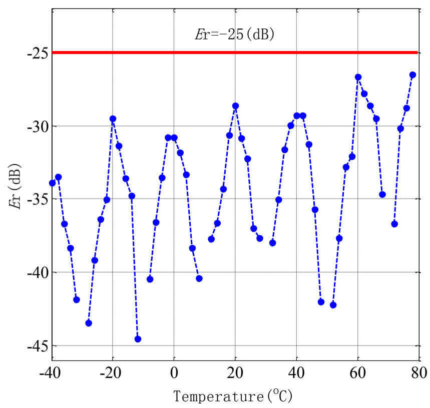


Figure 5 : Normalized errors at each temperature

3.2 Damage image with compensation method

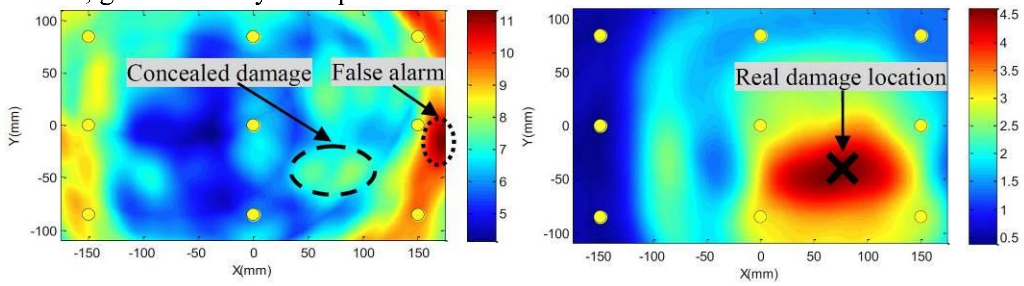
The delay-and-sum imaging algorithm [3] is applied in this section to determine the health status of the monitoring area. The actual damage is located in the center of the area surrounded by PZT 5, 6, 8 and 9. The coordinate of the actual damage is (-75mm, -42.5mm). With the signals recorded in the experiment, the compensation results are demonstrated as following.

(1) Image result without compensation

Under the influence of temperature variations, the algorithm cannot determine the right location of damage even the structure is damaged. An example is given: the baseline signal at 30°C is set to be Health Signal of the imaging algorithm, while the damage signal at 20°C is set to be Damage Signal. The imaging result shows a false alarm located in (172mm, -15mm) as demonstrated in Figure 6 a), while the actual damage location is concealed. The point with the pixel peak value of the imaging result is often regarded as the damage location.

(2) Image result with compensation

The ADALINE network is applied to compensate the reference baseline signal at 30°C to signal at 20°C. The compensational health signal at 20°C, which is the output of the network, is set to be Health Signal, while the damage signal at 20°C is set to be Damage Signal. The imaging result shows a damage in (-70mm, -44mm) as demonstrated in Figure 6 b). The result shows that after compensation, great accuracy is acquired with an error of 5.2mm.



a) Image result without compensation b) Image result with compensation

Figure 6 : Damage imaging results

Generally speaking, temperature effects will cause false alarms and conceal the damage information. After compensation, great accuracy is acquired with an error of 5.2mm. The proposed temperature compensation method is effective and has been verified by the damage detection.

CONCLUSION

In this paper, a new temperature compensation method based on adaptive filter ADALINE network has been developed to compensate for the amplitude-change and phase-shift of Lamb wave signals caused by temperature. The advantage of this temperature compensation method is that only 6 baseline signals are required for temperature range from -40°C to 80°C. Experiments are conducted on a stiffened carbon fiber composite panel to verify the temperature compensation method. Results show that with the proposed method, the temperature compensation scope can be set to 20°C. Damage image results shows that after compensation great accuracy for Lamb wave-based damage detection is achieved. This temperature compensation method can be applied for both composite structures and metallic structures. When this method is applied to a new structure, the weights for ADALINE network at each temperature should be re-trained with the data acquired in this new structure The next step of this research is to extend the present work for real composite structures with high geometric complexity.

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