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A Temperature Compensation Technique Based On Current Signal Reconstruction for Structural Health Monitoringusing Lamb Wave

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Abstract: Lamb wave structural health monitoring technique is widely used in aerospace, civil andmechanical engineering. However, this technique is easily affected by environmental condition variations, especially temperature variations. This paper presents a temperature compensation method for Lamb wave structural health monitoring systems.The proposed method is based on reconstruction of current signal in different temperatures. To do this, firstly, a linear relationship between the time of fight (TOF) and temperature variations is defined after the linear reconstruction of phase spectrum of collected signals. Then, by using Hilbert transform,the amplitude and phase of selected Lamb wave are extracted.Subsequently, a Phase factor is introduced by calculating thephase difference between the current signal and baseline. An amplitude factor is also introducedbased on the mean square error (MSE) of the baseline and current signals.Finally, by applying the phase and amplitude factors to current signal, the current signal is reconstructedinspecific temperature. The proposed method is validated both numerically and experimentally for an aluminum plate at different temperature range from 20℃ to 80℃.It is shown that, the error between the reconstructed current signal and baseline is much lower than that between the current signal and baseline before compensation. The results of several simulationand experimental tests demonstrate that this method can effectively remove the temperature variations effect of Lamb wave based SHM systems.

Keywords: Structural health monitoring, Lamb wave, temperature variation, linear reconstruction of phase spectrum, temperature compensation

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I. INTRODUCTION

In recent years, guided wave structure health monitoring has been widely used in the damage detection of aircraft structures and large buildings.[1-3] As an important SHM tool, the propagation process is complicated, and the multimodal and dispersion characteristics of Lamb wave make signal analysis more difficult.[4] The most commonly used damage judgement method is the baseline subtraction, which detects and locates the damage in the plate by using the linear characteristics changes such as attenuation, delay and waveform changes of the lamb wave.[5-7]When the environment or operating conditions change, this simple but effective method becomes a challenging task.[8,9]Temperature is an important environmental condition, the change of the temperature often causes the change of the instantaneous amplitude and phase of the signal, which may cause misjudgment if no valuable temperature compensation is applied.[10-11]

The most widely used temperature compensation techniques are the optimal baseline selection (OBS) and baseline signal stretch (BSS). OBS is a data-driven method, it needs to collect baseline signals within a certain temperature range to set up a database, and then select the best matching reference signal by using specific criteria for damage judgement.[12,13]OBS requires a large number of baseline signals and good temperature resolution to achieve a sufficiently low noise reduction. In practical applications, these important requirements are difficult to meet. Unlike OBS, BSS is a model-driven method, which seeks to establish a model to remove the effect of temperature.[14,15] The advantage of BSS is that only one baseline is needed to compensate the signal in certain temperature range. However, because the temperature range of BSS compensation is too small, it is not suitable for large temperature difference environment. And then, Clarke et al.[13] proposed a method of combining both OBS and BSS schemes to reduce the amount of baseline data needed for the temperature compensation. The method can be applied to practical engineering more effectively. Different from the OBS and BSS, Andrews et al.[16] proposed a scheme to reconstruct the first fundamental symmetric Lamb-wave mode (S_0) at different temperatures.The amount of phase-shift for individual frequency components in the signal was related to the changes in the mechanical stiffness of the base metal plate, which is affected by temperature variation. Roy and Lonkaret al.[17] proposeda novel method to reconstruct piezo-sensor signal by relating changes in the signal projection coefficients, as obtained from MP signal decomposition. The realization of the above methods is based on the known correlation coefficients such as material parameters and thermal expansion coefficients, but these conditions are difficult to obtain in complex structures.

Here we propose a novel reconstruction technique for the compensation of temperature influence on A_0 mode Lamb waves' snapshots.The reason of the change of Lamb wave signal caused by temperature change is obtained by theoretical derivation. Phase shift is the result of the change of Lamb wave velocity due to the change of materials' properties caused by temperature variation. It was found that the phase shift has a linear relationship with temperature difference in a specific interval. However, it is difficult to get the accurate time information due to the dispersion of Lamb wave.The proposed method consists of the following three steps. First, we select the direct wave packet to study, and thenuse the linear reconstruction of phase spectrum method to remove the dispersion and get the accurate time of flight(*TOF*), and then obtain the linear relationship between phase shift and temperature difference.Byapplyingphase compensation to the current signal to match the baseline signal in time domain,the amplitude factor is calculated by the mean square error (MSE) to complete the whole compensation.The results of numerical simulation and experiments all show that the proposed method can remove the bad effect of the temperature variation and improve the accuracy of SHM.

II. INFLUENCE OF TEMPERATURE ON LAMB WAVE PROPAGATION

Because of the multimodal and dispersion characteristics of Lamb wave, the dispersion effect is inevitable in the propagation process. The temperature variation will cause the change of instantaneous phase and instantaneous amplitude, and also the change of the shape of the wave packet, as shown in Fig.1. It is observed that the effective amplitude of the signal decreases with the increase of the propagation distance, the phase deviation between the two baseline signals increases, and the wave packet dispersion becomes more serious, as are shown in Fig.2.

The influence of temperature on wave propagation was demonstrated in Ref.[14]. For the reference signal at T_0, it can be demonstrated by considering an original signal：

$$u_0(t,T_0)=\sum_{j=1}^{N}A_j s(t-t_j) \tag{1}$$

Where u_0 is the signal comprised of the sum of various wave packet arrivals, with amplitude A_j, arrival time t_j and wave packet shape $s(t)$. After a temperature rises a different signal is received:

$$u_1(t,T)=\sum_{j=1}^{N}A_j s(t-(t_j+\delta t)) \tag{2}$$

Whereδt is the time shift caused by temperature variation.
According to the literature [21], the relationship betweenEqs.(1) and (2) can be expressed by

$$u_1(t)=A(t,T)u_0(\alpha(T)t) \tag{3}$$

Where$A(t,T)$ is an instantaneous amplitude factor at temperature T,and$\alpha(T)$ is a stretch-time coefficient.

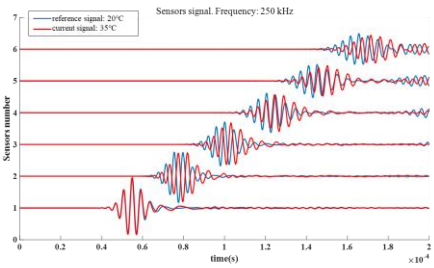

Fig 1. Illustration of the temperature effect on Lamb wave signals at different propagation distances.

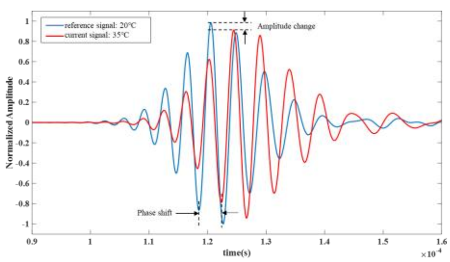

Fig 2. Illustration of the temperature effect on a Lamb wave signal.

III. PROPOSED TEMPERATURE COMPENSATION TECHNOLOGY

Temperature variation will cause the change of phase and amplitude of the Lamb wave signals, which may cause the misjudgment of damage. A novel temperature compensation is proposed herein to deal with this problem.Fig.3 shows the procedure for thetemperature compensation and signal reconstruction at specific temperature interval.

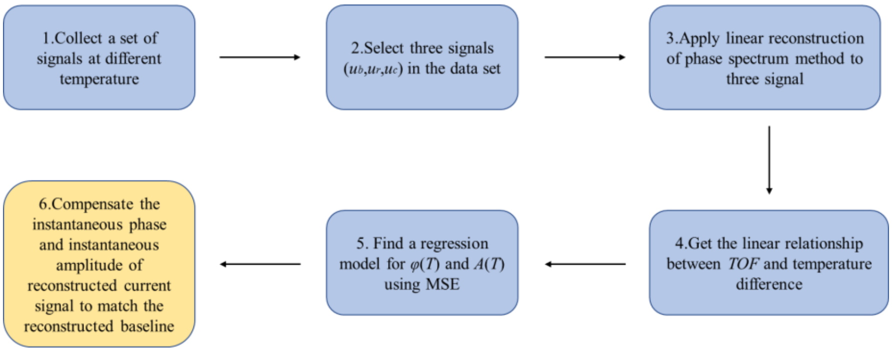

Fig.3 Proposed approach for temperature compensation.

3.1Proposed temperature compensation technology

Using the Hilbert transform, the instantaneous phase of the Lamb wave signal can be extracted[18]. So the signal can be expressed by

$$x(t)=u(t)+i\,\mathrm{H}\{u(t)\}=\hat{u}(t)e^{i\phi(t)} \qquad (4)$$

Where H{$u(t)$} is the Hilbert transform of the real signal. $\hat{u}(t)$ and $\Phi(t)$ are the amplitude envelope and instantaneous phase of the signal $u(t)$, respectively.

The analytic representation of the current signal is related to that of the baseline signal by

$$x_c(t)=A(t,T)\,x_b(t)e^{i(\phi_b-\phi_c)} \qquad (5)$$

WhereΦ_b and $\Phi_c$are the instantaneous phases of the baseline and current signal respectively.$x_b(t)$ is the baseline signal and $x_c(t)$ is the current signal at any temperature.

The reason for phase shift is that temperature variation changes the mechanical properties of the structure, leading to a variation of the wave velocity.The Young's modulus, density and Poisson ratio are important material properties that governs the velocity of shear and longitudinal waves in solid media. The variation in those material properties with temperature was obtained from the literature [19] and used in conjunction with well-known equations, which relate this to the shear and longitudinal velocities.[10] The relationship between temperature and the change in shear and longitudinal ultrasonic velocities is then given by

$$c_S=c_{S_0}+k_S(T-T_0) \qquad (6)$$

$$c_L=c_{L_0}+k_L(T-T_0) \qquad (7)$$

Where C_S and C_L are the shear and longitudinal velocity, $C_{S0}$and C_{L0} are the velocities at a reference temperature, k_S and k_L are the temperature dependence constants and T is the measured temperature.This indicates that the time of flight(TOF) of wave packets in Lamb wave signals has a good linear relationship versus temperature. So the instantaneous phase difference of the two Lamb wave signals with different temperatures is proportional to the temperature difference, within the limit range of temperature. This can be expressed by

$$\arg u_c(t)-\arg u_b(t)=\frac{T_c-T_b}{T_r-T_b}\left[\arg u_r(t)-\arg u_b(t)\right] \qquad (8)$$

Where T_b,$T_r$and T_c are the temperatures, $u_b(t)$,$u_r(t)$ and $u_c(t)$ are the Lamb wave signals at the temperature T_b,T_r and $T_c$respectively, and $u_b(t)$ is the baseline signal, $u_r(t)$ is the reference signal, and $u_c(t)$ is the current signal,*arg* denotes the instantaneous phase of the signal.

According to what is described above, the phase difference between baseline and current signal can be expressed by

$$\psi(t)=\phi_b-\phi_c=\beta\left[\arg u_r(t)-\arg u_b(t)\right] \qquad (9)$$

Where β is the factor that related to the temperatures of baseline, reference and current signal.Assuming constant values for $A(t,T)$ in a specific time window to compensate the amplitude difference between baseline and current signal, Eq(5) can be modified by

$$x_c(t)=A(T)\,x_b(t)e^{i\psi(t)} \qquad (10)$$

After amplitude correction and phase compensation from Eq(10), the real current signal $u_c(t)$ can be reconstructed from its analytical form as follows,

$$\tilde{u}_c(t)=\mathrm{Re}(x_c(t)) \qquad (11)$$

Where Re() is the real part.

3.2Linear reconstruction of phase spectrum based on Lamb wavesto remove dispersion

In practice, it is generally difficult for us to obtain accurate time information due to the dispersion of Lamb wave. In order to get the accurate time information to complete the temperature compensation, a removing dispersion method is proposed.The linear reconstruction of phase spectrum method is to obtain the phase spectrum of the measured signal by Fourier transform and linearize the phase spectrum at the center frequency to remove the dispersion effect in the signal. The measurement principle can be derived from the ultrasonic equation propagating in the medium.[20] Without considering the change of the environment, the expression for phase velocity measurement can be expressed by

$$c_p = \frac{\omega(x_2 - x_1)}{\varphi_2(\omega) - \varphi_1(\omega)} \tag{12}$$

where x_1 and x_2 are the propagation distances, $\varphi_1(\omega)$ and $\varphi_2(\omega)$ are the phase spectrum of Lamb wave propagating x_1、 x_2 ($x_1 < x_2$), respectively.

The group velocity of Lamb wave in a medium can be expressed by the differential form of frequency to wave number:

$$c_g = \frac{d\omega}{dk} \tag{13}$$

Wave number k can be expressed by phase spectrum:

$$k = \frac{\varphi(\omega)}{x} \tag{14}$$

Combine Eqs. (13) and (14), the relation between the change rate of phase spectrum and group velocity and propagation distance can be obtained:

$$c_{\mathrm{g}} = \frac{d\omega}{d\varphi(\omega)} x, \quad \frac{d\varphi(\omega)}{d\omega} = \frac{x}{c_{\mathrm{g}}} \tag{15}$$

From the above Eq.(15), we can know that the phase spectrum of the signal propagates x distance and has a certain value to the frequency, and the phase spectrum changes linearly with the frequency if the detection signal has no dispersion, that is $c_g$is independent of f. Fig.4 shows the non-dispersive time-domain signal propagating at a certain distance. The waveform features remain unchanged and the propagation time information of the wave packet signal can be accurately extracted. The phase spectrum of the signal after Fourier transform is shown in Fig. 5. The phase spectrum of the non-dispersive signal is linearly related to the frequency.

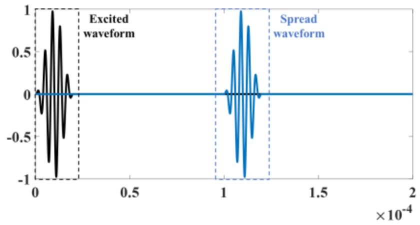

Fig.4 Non-dispersion signal

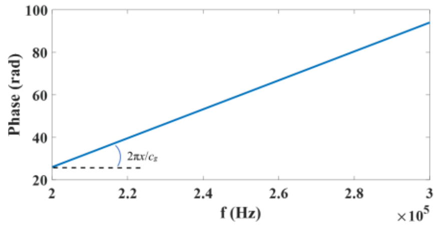

Fig.5 The phase spectrum

If the signal exists dispersion, c_g in Eq.(15) is no longer a constant f. The differential of phase spectrum is related to the corresponding group velocity at different frequencies:

$$\frac{d\varphi(\omega)}{d\omega} = \frac{x}{c_g(\omega)} \tag{16}$$

From Eq.(16) we know that the differential of the signal phase spectrum to the frequency is no longer a definite value after the propagation x distance when the signal exists dispersion, and its value is related to the group velocity at different frequencies, so the phase spectrum and the frequency are no longer linear.

Based on the above analysis, a linear reconstruction of a phase spectrum method is proposed.This method does not require the known dispersion relationship and material characteristics. As long as the phase spectrum of the detection signal is linearized at the central frequency, the nonlinearity of the phase change caused by the dispersion can be eliminated. And then we can get the accurate TOF information of each signal.

3.3 The specific process of the proposed temperature compensation

The overall specific process is described by the following sequential steps:

1. Remove the dispersion of the direct wave to get accurate TOF information by using the linear

reconstruction of phase spectrum method. The procedure is as follows:
(1)The spectrum and phase spectrum of time domain signal $f(t)$ are obtained by Fourier transform;
(2)By unwrapping the resulting phase spectrum, get the phase spectrum shown in Fig.6 (real line);
(3)The phase spectrum is linearized at the center frequency to eliminate the phase nonlinear variation caused by dispersion, and the linear phase spectrum shown by the dashed line in Fig. 6 is obtained;
(4)The linearized phase spectrum and spectrum are taken as the elements of the reconstructed signal. The time-domain signal *fnon* (t), without dispersion is obtained by inverse Fourier transform as shown in Fig. 7.

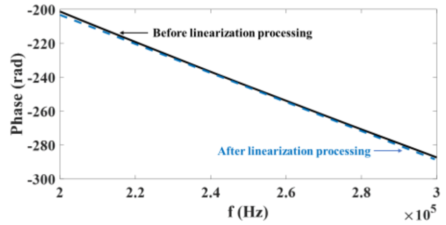

Fig.6The phase spectrum after reconstruction

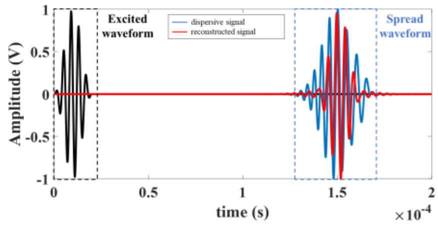

Fig.7 Signal after reconstruction

2. Determine the operating range of temperature wherein linear functional relationship between changes in signal amplitude and material properties would exist. This could be done by using numerical simulations and knowledge of temperature-dependent material properties.
3. Collect a set of reconstructed signals at different temperatures and build the signal database *M*.
4. Apply Hilbert transform to the real signal to get the envelop of the signals and analyze them.
5. Select three signals from the database torepresent baseline signal, reference signal and current signal, respectively. And then isolate direct wave packets from the sensor measurements and get their time of flight (TOF). TOF is referred to as the time corresponding to the peak of the envelop which is the Hilbert transform of the reconstructed signal packets.
6. Assuming phase shift to vary linearly with temperature,calculate the current signal's phase factor$\psi(t)$ according to Eq.(9).
7. Applying amplitude factor A(t) to the reconstructed current signal by Eq.(10), estimate the value by calculating the mean square error (MSE) between reconstructed baseline and current signal.

$$MSE(x)=\frac{1}{\Delta L}\int_{L_1}^{L_2}\left(x_b(t)-x_c(t)\right)^2 dt \tag{17}$$

WhereL_1 and L_2 are the beginning and the end of the direct waveform, respectively. ΔL is the width of the direct waveform,$\Delta L=L_2-L_1$. The larger the MSE value, the lower the similarity between the two signals.

8. After phase and amplitude compensation, take the real part of the reconstructed current signal according to Eq.(11) and complete the process of temperature compensation.
9. Finally, the Error[15]between the two signals is calculated to determine whether the current signal is damaged or not.

IV. FINITE ELEMENT SIMULATION AND ANALYSIS ON ALUMINUM PLATE

Building a three-dimensional aluminum plate (800mm×800mm×2mm) model in COMSOL. In the numerical model, the equivalent force line is used instead of piezoelectric transducer to excite ultrasonic Lamb wave signal without considering the shear delay effect of the bond layer. Time-trace simulations based on the properties of the A_0 Lamb wave mode in the plate excited with a 5 cycle Hanning windowed tone-burst with 250kHz center frequency is considered. In order to improve the computational efficiency, only a quarter of the simplified model is considered in the simulation. The propagation of Lamb waves in an infinite plate is simulated by setting symmetrical and absorbing boundaries.

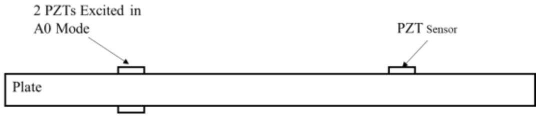

Fig.8 Numerical simulation plate model

The effect of temperature on elastic modulus, density and Poisson's ratio is considered in the calculation. The material parameters of 6061 aluminum alloy with temperature are obtained fromreference[19]. The temperature range is 20~70 ℃, and the interval is 1 ℃, 51 groups of baseline signals are obtained. During the simulation, the signal is activated at the center. The temperature compensation method is evaluated by comparing the nondestructive signals at different temperatures.

According to the reference[10], it is known that the residual signal amplitude obtained by subtracting the baseline signal from the current signal should be greater than – 40 dB, so that the signal-to-noise ratio can be high enough to effectively identify the signal changes caused by structural defect. The signal is studied and - 40 dB is selected as the target value.

The direct wave packet is carried out to be analyzed during the process of the proposed method.The goal is to avoid the effects of the boundary reflection.A typical signal is shown in Fig.9(a), resulting from the tone-burst actuation waveform at 250kHz. Use the Hilbert transform to get the envelop of the received signal and then get the *TOF* information, as shown in Fig.9(b). Fig.9(c) plots the TOF data of the wave packets at different temperatures before any signal processing. These points are distributed on both sides of the line, but the degree of dispersion is too high to be regarded as linear fitting. Fig.9(d) shows that these points follow an anticipated linear trend after the original signals have had the linear reconstruction of phase spectrum, from which the phase factor could be calculated.

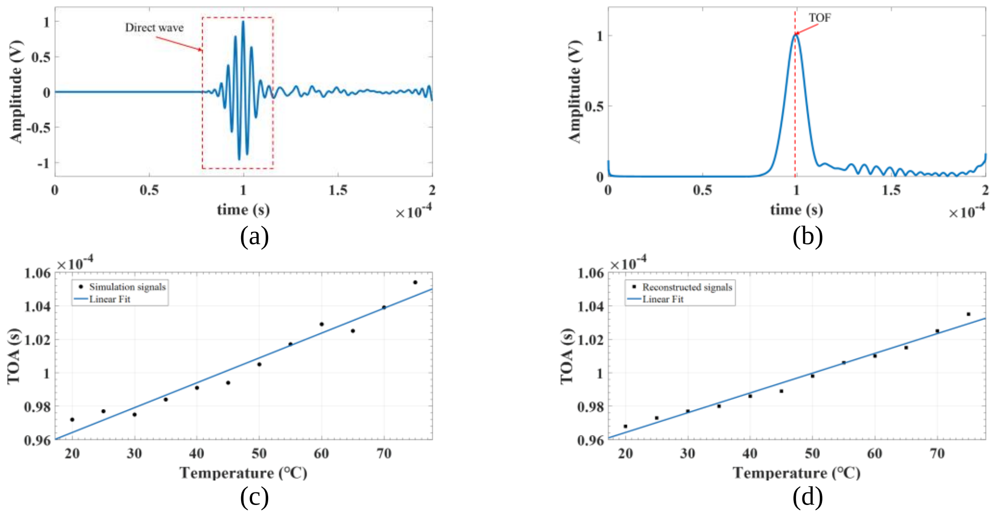

Fig.9 (a) Received signal at 250kHz in the simulation, (b) The Hilbert transform of the received signal, (c) Simulation signals' TOF variation with temperature, (d) Reconstruction signals' TOF with temperature.

The examination of the results shows that: the maximum temperature interval compensated by BSS is 5 ℃, indicating that the actual compensation range is 2.5℃ above and below the baseline signal temperature.[13-15]So, 40℃ and 42℃ are selected to be compared, as shown in Fig.10a. The noise levels in the subtracted signal are shown in Fig.10b and correspond to a worst case of -36.6 dB. This value is higher than the target value -40 dB, which demonstrates that the temperature compensation is indispensable although the temperature changes are very small. Fig.10c shows the baseline and the current signal after reconstruction, in which the reconstructed signals all remove the dispersion, and the current signal matches the baseline finely. The maximum residual signal value is -43.9 dB lower than -40dB.

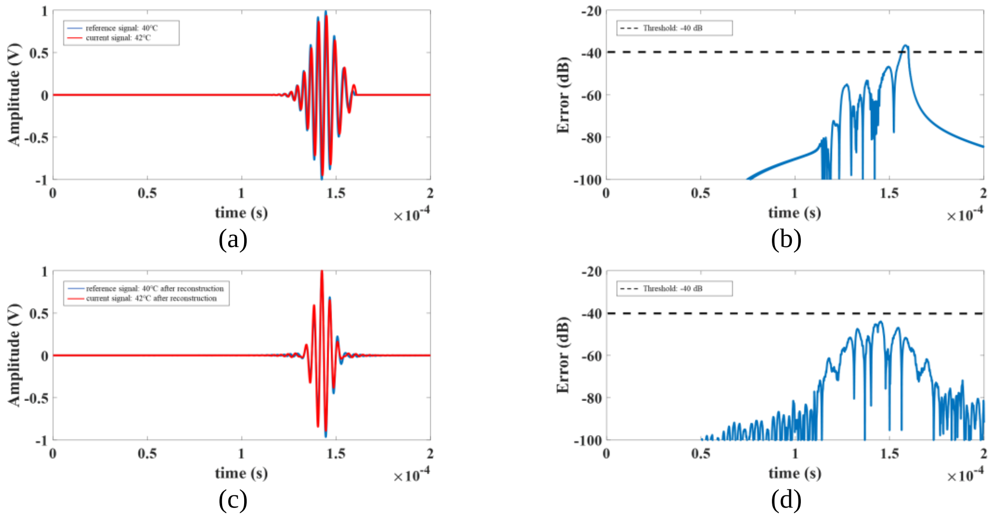

Fig.10 (a)40℃and 42℃baseline signal, (b) the Error of the residual signal,(c) reconstructed 40℃and 42℃baseline signal, (d) the Error of the residual signal after compensation.

When the temperature interval is 5℃, it is demonstrated that the proposed method is still useful by comparing with the condition of current signal after BSS compensating at different distances. Using MSE as the standard to judge the coherence between baseline and the compensated signal, as shown in table 1.

Table 1 Coherence between baseline and the compensated signal at the interval of 5℃

Propagation distance (mm)	Mean Square Error		
x	Original	BSS	Reconstruction
141	0.57	0.06	0.03
283	0.72	0.11	0.07
424	0.82	0.68	0.12

The compensation effect of BBS becomes worse with the increase of propagation distance. Although the reconstruction method also has the same problem, butit still achieves the goal of compensation. This demonstrates that the reconstruction method has better adaptability under the influence of increasing propagation distance.

Fig.11a and b show the residual levels after subtraction of signals with a temperature interval of 10 ℃. As the temperature increases, the width of the signal also changes, the width of the baseline is 464μs but the current signal width is 499μs, as shown in Fig.11a. The worst amplitude level in the residual signal after the direct subtraction between a signal taken at 60 ℃ and a baseline at 50 ℃ was -27.0 dB relative to the first arrival, which is much poorer than the target value. After the reconstruction method is applied, the residual level obtained after the subtraction is shown in Fig.11. A worst value of -44.9 dB relative to the first arrival was found. Meanwhile, the shapes of signals are still the shape of the excitation signal after a long distance. This again demonstrates that the proposed method can remove the effect of temperature variation effectively, not only in small temperature difference and short propagation distance but also in large temperature difference and long distance.

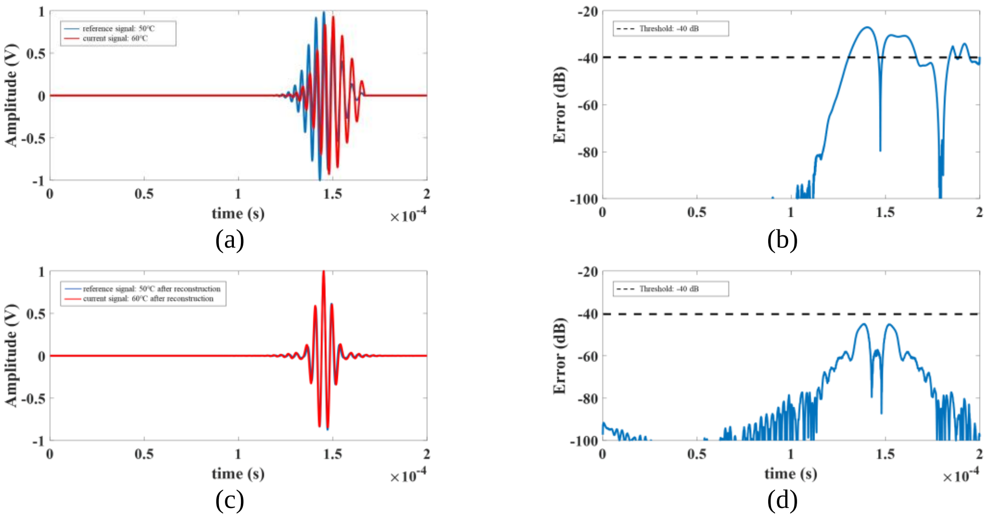

Fig11 (a)50℃ and 60℃ baseline signal, (b) the Error of the residual signal,(c) reconstructed 50℃ and 60℃ baseline signal, (d) the Error of the residual signal after compensation.

V. EXPERIMENT PART

5.1 Experimental setup

The experimental set up includes a 6061aluminum plate, 1m×1m×1mm, instrumented with a rectangular smart heating layer. Change of temperature was made by the heating layer, using PZTs to excite an A_0 mode signal and recording the signals of different temperatures by scanning laser Doppler vibrometry (SLDV), as shown in Fig.12.

(a) (b)

Fig.12 (a)The setup of experiment, (b)the flexible Silicone rubber heater

Lamb waves were symmetrically excited by a pair of PZTs at the center of the plate and recorded by laser scanning using SLDV. Piezoelectric elements are actuated with a five-cycle sinusoidal tone burst at a central frequency of f_0, which is modulated by a Hanning window. In the following, the excitation frequency is set to f_0=250kHz, and the excitation signal is generated by a Waveform Generator, and amplified to 10V using a voltage amplifier from FLC Electronics.

The particular features of this setup include large propagation distances and the possibility of controlled heating over a range of temperatures, up to 70℃. These characteristics enabled a better study into the physical phenomena analysis. Both artificial heating and room temperature were considered. Artificial heating was introduced through a flexible Silicone rubber heater that was placed in the middle of the plate, powered through 500W DC source and the control interval is 1℃.

Finally, the signal is collected by means of laser scanning by controlling the SLDV. The benefits of the SLDV are that it can record signals at any point on the plate and SLDV is less affected by temperature changes of components than PZT sensors in the process of receiving signals, because the properties of the PZT sensor are easily affected by temperature variations, such as the Young's and shear moduli that will affect the velocity and the energy of the signal in the process of propagation and make the instantaneous amplitude and phase change so that affect the accuracy of SHM.

5.2 Signal analysis and compensation

When the temperature difference is 3 ℃, the baseline (25 ℃) and the "severe defect" signal (22 ℃) are shown in Fig.13a. Because the defect is severe the reflection from the defect is strong.It is easy to detect the defect, but the accurate propagation time information could not be obtained due to the dispersion of the defect signal packet. The maximum residual signal level obtained by directly subtracting the two signals is -28.2dB as shown in Fig.13b. Although the residual level is higher than -40dB, but the level contains the effects of defect and temperature change together, it does not accurately prove the existence of defect. Using the reconstruction method to compensate signals and the resultsare shown in Fig.13c. It can be seen from the figure that the shapes of the baseline and current signal all restored to the original signal and also the "defect" packet is obviously detected and the time information can be accurately acquired after compensation. Fig.13d shows the worst residual level of the subtracting reconstructed signals is -29.7dB. This value is only the information produced by the defect and proves the defect is existed. This illustrates that the proposed method effectively identifies the structural defect at the different temperatures.

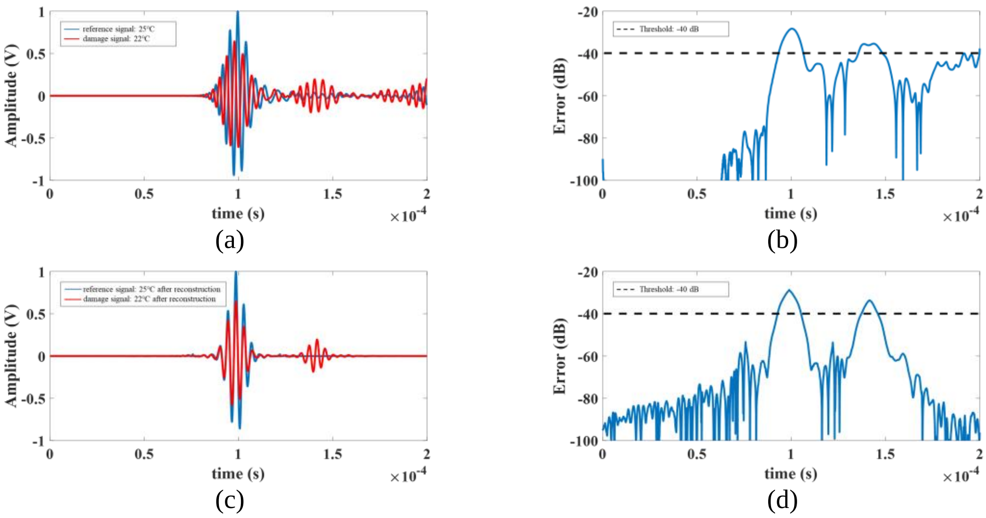

Fig.13 (a)25℃baseline and 22℃damage signal, (b) the Error of the residual signal,(c) reconstructed 25℃baseline and 20℃damage signal, (d) the Error of the residual signal after compensation.

The above multi group studies can demonstrate that the linear reconstruction of phase spectrum temperature compensation is able to remove the effect of dispersion and temperature variation effectively and identify the defect accurately for both severe and light defects. On the other hand, it can expand the range of temperature differences and improve the efficiency of SHM.

VI. CONCLUSION

A new method to compensate for the influence of temperature on Lamb waves snapshots has been proposed.It explores the underlying causes of the change in signal phase and amplitude caused by temperature change. The instantaneous phase shift is attributed to the change of the velocity of Lamb wave, the essence is the temperature variation causes the change of the material properties. The amplitude change can be concluded as the change of the energy during the Lamb wave propagation. Combining the data-driven method and model-driven method to remove the effect of temperature variation.

The methodcompensates the current signal to match the baseline signal by applying the phase compensation and amplitude compensation to the current signal independently. Itconsists of three major parts, the first part is to get the accurate TOF information of received signals at different temperatures for which, the direct wave packets are selected and used to find the relationship between TOF and temperature. The second part is the process of phase compensation,using Hilbert transform to extract related phase shift information due to the fact that the reconstructed signals' TOF is linear with temperature, and to estimate the phase factor. Finally, estimating the amplitude factor by calculating the MSE between the reconstructed current signal and the model baseline signal.

The present technique has showed good performance in simulation signals and experimental signals.Not only the effect of the temperature could be removed, but also the residual signal is more accurate than the results obtained from the original baseline subtraction. Although the investigated setup and subject was relatively simple, the method is expected to operate well in more complex structures which will be tested in further steps.

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