Temperature Compensation Based on Hilbert Transform and Instantaneous Phase for Lamb Waves-Based SHM Systems of Aircraft Structures

L. AMBROZINSKI, P. MAGDA, K. DRAGAN, T. STEPINSKI and T. UHL

ABSTRACT

Variation of environmental conditions, e.g. temperature, influence wave propagation and therefore can create serious issues limiting application of guided waves (GW) in SHM systems. Temperature variations cause a change of wave velocity, which can be observed as a signal stretching. Therefore, although no damage occurs, the signal captured during the monitoring process, does not match the baseline signal. This may lead to frequent false alarms if the alarm level is low or to disregarding damage if the alarm level is too high.

In this paper a novel method for compensation of the temperature influence on Lamb wave snapshots is presented. The first step of the technique relies on the calculation of signal's instantaneous phase using Hilbert transform. Next, phase of the resulting complex analytic signal is shifted to match the phase of the baseline signal. Finally, the inverse Hilbert transform is applied to the result, which leads to aligned of the instantaneous phase of both waveforms.

INTRODUCTION

The problem of health monitoring of aircraft structures still comprises many unsolved issues. The spectrum of variable loads that affect the structure depends first and foremost on the way the aircraft is operated, hence, there is no chance to precisely design the aircraft life before it enters the operational use [1]. Therefore, using SHM systems that are integrated with the structure can give considerable benefits such as shortening the maintenance time and increasing the safety level at the same time. Many aircraft components are thin-walled elements, thus, they can be monitored using Lamb waves (LW). LWs are particularly attractive due to the long range propagation ability and sensitivity to structural integrity changes. However, due to dispersive character and multimode nature of these waves, the acquired signals are very complex.

L. Ambrozinski, P. Magda, K. Dragan, T. Stepinski, T. Uhl, AGH-University of Science and Technology, Krakow, Poland

K. Dragan, Air Force Institute of Technology, ul. Ks. Boleslawa 6, 01-494 Warsaw, Poland

In real applications, for instance testing of aircraft components with riveted joints, stringers and complex geometries, it is usually difficult to distinguish damage reflected signals from the boundary reflections; therefore, monitoring normally involves a set of baseline signals captured on a healthy structure. The signals acquired during operation are compared with the baselines and damage indices (DI) are calculated. DIs are supposed to describe the condition of the monitored element [2]. Although, this approach can be successfully used to remove reflections from the unwanted boundaries, it becomes impractical when environmental or operational conditions change [3].

Temperature is an environmental property that is most commonly altered during the monitoring process. Variations in temperature cause thermal expansion and influence material properties of the material, which influences wave velocity and can be observed as signal stretching [4, 5]. Comparing the baselines with temperature affected signals results in high DIs levels, which can lead to false alarms or override presence of a damage. Therefore, it is important for the SHM systems to distinguish damage features from other effects.

Several methods for temperature influence on GWs compensation have been already proposed. The techniques can be roughly divided into two categories: optimal baseline subtraction (OBS) and baseline signal stretch (BSS).

The OBS, is a data-driven approach since it uses a collection of baselines recorded over a range of temperatures [4, 6]. In the monitoring process a DI is calculated by a comparison of the current-state signal with the baseline time-trace, which best matches the recent snapshot. Possible criteria to find the best-matched baseline are mean square deviation between the snapshots [4] or maximum residual amplitude after the signals subtraction [3].

The BSS techniques are based on a model of the effects of temperature change on wave's propagation. It assumes that the temperature influences wave velocity which results in difference of time of flight (TOF) of the subsequent wave packets. The delay increases with time, therefore signal stretching can be observed. These methods, unlike the OBS, require in their simplest implementation only one baseline signal. An example of a technique based on time-stretch model is local-time coherence difference (LTCD). The LTCD can be considered as a measure of the time-dependent shape change between two signals [7]. Other BSS methods simply modify the time-axis of the baseline time-traces. One of the possible approaches uses FFT for data resampling and the stretching is performed in time domain yielding nonuniformly sampled data [8]. Recently a stretched-based temperature compensation method based on scale transform was proposed [9].

Here, we propose a novel BSS technique that for compensation of temperature influence on Lamb waves' snapshots. Based on the model of temperature influence on Lamb waves propagation, it can be assumed that the delay between the temperature affected baselines increases with time [4]. This effect can be observed as a change of the instantaneous phase of the signals [5]. The proposed scheme consists of two steps: first, the instantaneous phase of the snapshot is estimated using Hilbert transform and it is aligned with that of the baseline in the second step. After phase alignment in the second step the snapshot is stretched and the temperature influence is compensated.

This paper is organized as follows: first a brief theoretical background of the proposed technique is outlined, next experimental setup is described. Successively, the influence of the temperature and damage on LWs snapshots is discussed, followed by result of the proposed compensation strategy application. Finally conclusions are drawn.

THEORETICAL BACKGROUND

There are a number of temperature-related effects that affect a GW-based SHM system performance. Some of them are related to temperature dependence of the transducers' parameters and properties of the adhesive coupling. These effects can be usually observed as a variation in signal amplitude. However, only phenomena that contribute to temperature dependence of GW's propagation are considered here; namely, the thermal expansion or contraction that alters the propagation distance and influences material properties and appears as a change of wave velocity. Based on these consequences it can be assumed that a temperature effect on a GW signal can be approximated by a time-stretch of the time signal *x(t)*

$$x(t) \xrightarrow{Temp} x(\alpha \cdot t) \tag{1}$$

where α is the stretching constant [9]. This shift can be observed as a change in instantaneous phase of the signal and Hilbert transform can be used as a tool to extract that feature [5]. Using this approach leads to an analytical complex signal

$$z(t) = A(t) \cdot e^{i\phi(t)}, \tag{2}$$

where $\phi(t)$ is the phase of the signal.

If a snapshot is affected just by the temperature, only phase of the signal is expected to change. Therefore, the influence of the temperature can be eliminated if the instantaneous phases of the baseline and the current signal are aligned. The phase of the signal can be modified simply using the following relation

$$z'(t) = z(t) \cdot e^{i(\phi_B(t) - \phi(t))}, \tag{3}$$

where $\phi_B(t)$ is instantaneous phase of the baseline.

After phase alignment, the snapshots can be converted from its analytical form back to the time domain, yielding stretched signals with temperature influence compensated.

The compensation, however, is only for the differences in wave propagation and does not take into account the effects related to the fluctuations in performance of transducers. In order to make the SHM system insensitive to amplitude fluctuations, the DI was proposed as

$$DI = 1 - \frac{\int_0^T [x(t) - \mu_x][y(t) - \mu_y] dt}{\sigma_x \sigma_y}, \tag{4}$$

where *x(t)* and *y'(t)* are baseline and current state signal with modified phase respectively; σ is standard deviation and μ stands for mean of the corresponding signals. Therefore, the condition of the structure is calculated as a difference between unity and normalized cross-correlation coefficient of phase-matched signals. Since the phase difference is compensated and the normalized cross-correlation is insensitive to amplitude change, only fluctuations of the overall waveform shape are expected to give large DI's values.

EXPERIMENTAL SETUP

The experiments were conducted using an aluminum plate of dimensions of 320 mm x 300 mm x 1 mm shown in Figure 1. Four identical piezoelectric transducers (PZT) were attached to the top of the experimental object with cyanoacrylate adhesive according to the layout presented in Figure 1. The transducers used during the research had 7mm diameter and the 0.3mm thickness, resonant frequency at 300kHz. They were manufactured by STEIMIC PIEZO USA and depending on the configuration; they served as an emitter or sensor. A 5 cycle tone burst with center frequency at 300kHz, modulated with Hanning window was used as an excitation. The acquisition was performed with sampling rate of 2.5MHz and resolution of 24 bits. The signals were generated and acquired by PAQ 16000D manufactured by EC Electronics, Poland. The temperature was registered by multi-meter AXIOMET AX-594 equipped with thermocouple with accuracy $\pm 1^{o}$C.

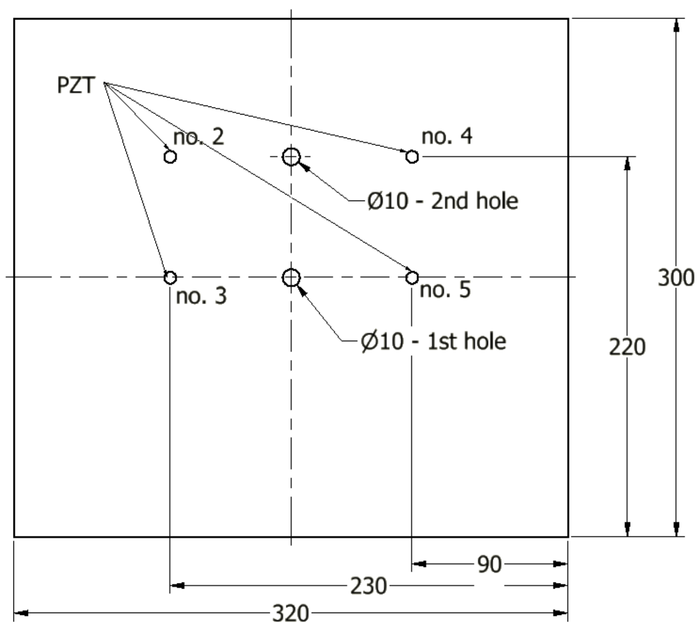

Figure 1. The specimen used in the experiment

The experiment was designed to imitate a monitoring process. The aim of the first part was to investigate the influence of temperature variations on waves' propagation in the undamaged plate and to collect baselines. A set of 389 snapshots was recorded within 10 minutes period, whereas the temperature was varying in the range from $+8^{o}$C to $+23^{o}$C. The registered temperatures are presented in Figure 2.

TABLE I. SUMMARY OF THE MEASUREMENTS

Waveform description	number of waveforms	temperature range [°C]	1st hole diameter [mm]	2nd hole diameter [mm]
Baseline	389	8-23	N/A	N/A
Damage (1st hole)	31	21-23	3-10	N/A
Damage (2nd hole)	25	23	10	3-10

In the second step of the experiment, drilled holes were introduced to the monitored aluminum plate. The distribution of the artificial flaws is presented in Figure 1. Drilling started from 1st hole - from diameter of 3 mm and it was enlarged with 1mm step to 10 mm. Subsequently, the second hole was introduced in the same way. Measurements were captured at the increasing damage levels. The number of the acquired waveforms and the description of structure's condition that occurred during the experiment, were summarized in Table I.

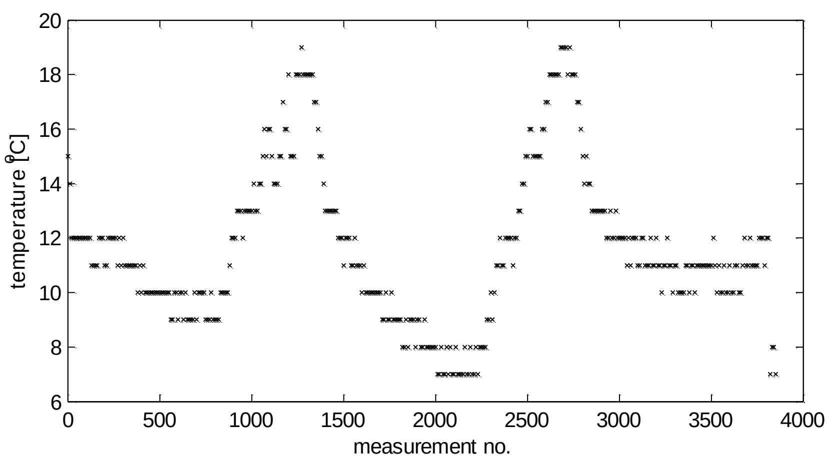

Figure 2. Temperature registered during the first stage of the experiment

RESULTS

In the following, divided into two parts section, results of the conducted experiments will be presented. First, the influence of temperature change and damage on the time signals will be discussed, followed by examples of the compensation strategy. Next, damage indices calculated for temperature influenced signals before and after compensation will be compared.

Influence of temperature on time signals

In order to illustrate the influence of temperature variations on Lamb waves propagation, an example of snapshots acquired along the path 3-5 is presented in Figure 3a. Although no damage was introduced to the structure, the signals differ, both in phase and amplitude. Therefore, a simple subtraction of the signals will lead to a significant residual waveform. The phase difference is a result of wave velocity variation, whereas the change of amplitude can be explained by the influence of the temperature on the transducers and the adhesive.

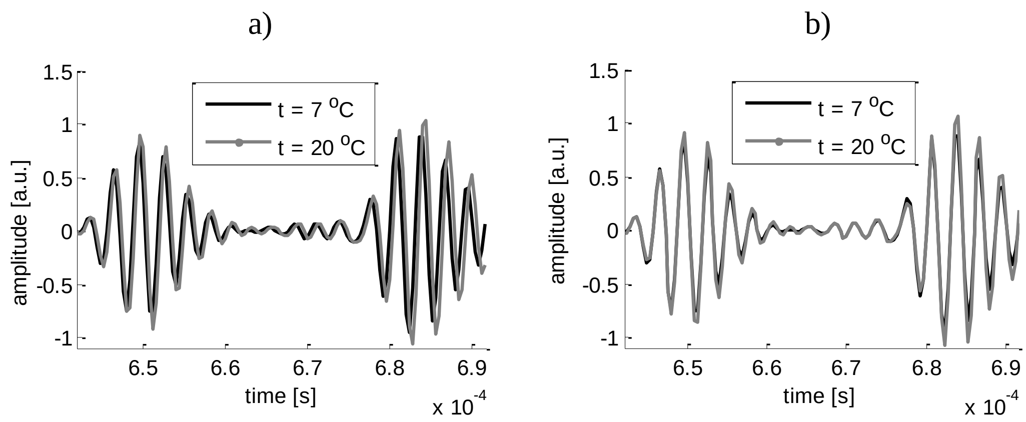

Figure 3. Example of time signals acquired for an intact plate a) affected by temperature change b) after compensation.

The proposed compensation method was applied to the signal captured at 20°C bringing its phase to the signal acquired at 7°C. From Figure 3b it can be observed, that the resulting waveforms exhibit only a slight difference in amplitude. This discrepancy can be still an issue for certain signals similarity measures, however, since in the proposed approach normalized cross correlation coefficient is used, it is expected that only difference in shape of the overall signals will result in high DIs values.

The change of the signal caused by the discontinuity occurrence can be observed in Figure 4a. The measurements were performed by the transducers pair 3-5, therefore, the drill hole was along the propagation path. From the Figure 4a it can be seen that although the snapshots were taken in similar temperature, the damaged signal is slightly delayed with respect to the baseline. It can be explained in this case with longer propagation distance. Moreover, a significant change of the second wave-packet shape can be observed.

The damaged signal was subject to compensation procedure and as it can be seen from Figure 4b, its phase is aligned with the baseline. However, the similarity of the 10mm hole signal with the baseline is poorer that between the signals presented in Figure 3b.

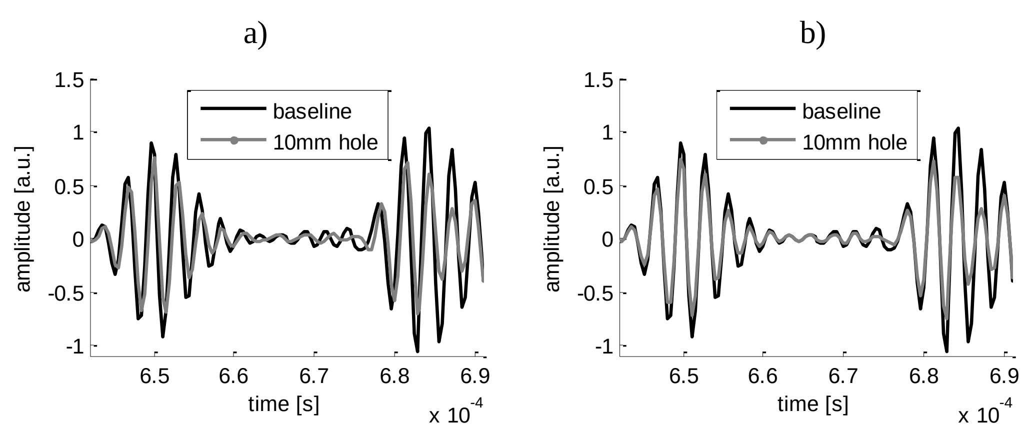

Figure 4 a) Comparison of baseline and damaged signals acquired at room temperatures b) result of the compensation procedure applied to the damaged signal.

Damage indices

In order to present the robustness of the proposed damage detection strategy, all of 445 signals, acquired during the experiments, were used to calculate the DIs. Therefore, the analyzed data included the temperature corrupted and damage-related snapshots.

The first signal, captured at 23^0C, was considered as a baseline. The raw data was processed to calculate the DIs as a difference between the unity and the normalized cross correlation coefficient between the baseline and the successive signals. The operation was repeated in the next step, however, the DIs were calculated as a drop of correlation coefficient between the baseline and temperature-compensated waveforms.

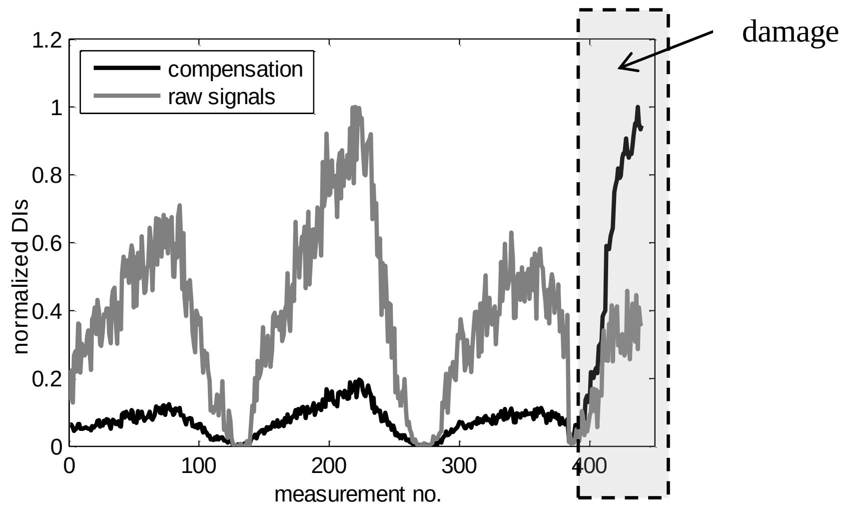

Figure 5. Comparison of damage indices calculated using cross correlation between the raw and the temperature-compensated signals. The measurements with gray background were taken for the damaged plate.

The aim of SHM systems is to distinguish between the damaged and not damaged state of the structure. Normally, a threshold value is used to separate these indications; therefore, not the absolute values of DIs are important, but relative differences between the damaged and undamaged features. Therefore, the obtained sets of DIs were divided by their maximum values to make possible comparison of these two approaches. From the results, presented in Figure 5, it can be seen that the raw signals are highly sensitive to temperature variations and the temperature-corrupted data give higher DIs than signals captured for a damaged structure. Therefore, using this approach the damage would be concealed by the environmental effects.

The robustness of the presented approach ascends when compensation is used. The DIs values obtained for the biggest hole are approximately 5 times higher than the highest values caused by the temperature variation.

CONCLUSIONS

A new method to compensate for the influence of temperature on Lamb waves snapshots was proposed. It was shown, that using the compensation strategy can considerably improve robustness of the GWs-based SHM system.

In the proposed method analytical form of the signals is used to modify the instantaneous phase of the current snapshot to match the baseline. The signals with the aligned phase are used to calculate the DI using normalized cross-correlation coefficient. After the compensation the phase of the measured signal is replaced by the phase of baseline. Since it is a significant modification of the waveform, some damage-related features can be lost. Hence, the length of the signal used for analysis has influence on the result and should be carefully selected.

The presented technique showed good performance in damage assessment of an aluminum plate. Although the investigated setup was relatively simple, the method is expected to operate well in more complex structures which will be tested in further steps. Moreover, the proposed method is a stretching technique and its performance can be additionally improved by combination with OBS, which will be tested in further steps.

ACKNOWLEDGEMENT

Authors would like to thank the NCBIR for supporting of the work which has been realized under the LIDER project LIDER/25/43/L-2/10/NCBiR/2011 based on the agreement from the 09.08.2011.

REFERENCES

[1] P. NMAB-488-2, “Aging of U.S. Air Force Aircraft, Final Report,” tech. rep., National Academy Press, USA, Washington D.C., 1997.

[2] C. Y. Park, “Damage index comparison for a composite stiffened panel using Lamb waves,” *Advanced Materials Research*, vol. 26 - 28, pp. 1265–1268, 2007.

[3] T. Clarke, F. Simonetti, and P. Cawley, “Guided wave health monitoring of complex structures by sparse array systems: Influence of temperature changes on performance,” *Journal of Sound and Vibration*, vol. 329, no. 12, pp. 2306 – 2322, 2010

[4] Y. Lu and J. E. Michaels, “A methodology for structural health monitoring with diffuse ultrasonic waves in the presence of temperature variations,” *Ultrasonics*, vol. 43, no. 9, pp. 717 – 731, 2005.

[5] P. Kijanka, R. Radecki, P. Packo, W. J. Staszewski, and T. Uhl, “GPU-based local interaction simulation approach for simplified temperature effect modelling in Lamb wave propagation used for damage detection,” *Smart Materials and Structures*, vol. 22, no. 3, p. 035014, 2013.

[6] G. Konstantinidis, B. W. Drinkwater, and P. D. Wilcox, “The temperature stability of guided wave structural health monitoring systems,” *Smart Materials and Structures*, vol. 15, no. 4, p. 967, 2006.

[7] J. Michaels and T. Michaels, “Detection of structural damage from the local temporal coherence of diffuse ultrasonic signals,” *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 52, no. 10, pp. 1769–1782, 2005.

[8] A. J. Croxford, J. Moll, P. D. Wilcox, and J. E. Michaels, “Efficient temperature compensation strategies for guided wave structural health monitoring,” *Ultrasonics*, vol. 50, pp. 517 – 528, 2010.

[9] J. Harley and J. Moura, “Scale transform signal processing for optimal ultrasonic temperature compensation,” *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 59, no. 10, pp. 2226–2236, 2012.