Efficient Acquisition of Baseline Signals in Ultrasonic Guided Wave Structural Health Monitoring (SHM)

Osvaldas PUTKIS¹, Anthony J. CROXFORD¹

¹Mechanical Engineering Department, University of Bristol; Bristol, UK
o.putkis@bristol.ac.uk, a.j.croxford@bristol.ac.uk

Abstract
Temperature compensation methods – Optimal Baseline Selection (OBS) and Optimal Stretch Method (OSM) – have been successfully used to suppress temperature effects in ultrasonic guided wave signals. However, the methods require a set of baseline signals recorded on an undamaged structure at a range of temperatures before SHM can be realised. This is difficult to achieve on structures exposed to real environmental conditions when there is limited control or knowledge of temperature variations. Therefore, a novel algorithm has been designed that continuously builds a set of baseline signals well separated in the temperature domain without having any information on the structure operating conditions. The performance when differentiating between damage and temperature effects in the signals based on sensor array images and baseline set growth parameters have been tested with data from SHM experiments. This makes the acquisition of baseline signals an evolutionary process which can be incorporated into SHM.

Keywords: Structural Health Monitoring (SHM), guided wave, temperature compensation, baseline

1 Introduction

There is a growing interest in the development of SHM systems in various industrial sectors (aerospace, nuclear, gas and oil, and other) and a considerable research effort is being made in search for reliable and cost-effective implementations of SHM systems for various applications.[1, 2, 3, 4] Unlike conventional Non-Destructive Evaluation (NDE) techniques SHM systems are designed with sensor networks permanently attached to the structures that continuously observe relative changes to the state of the structure using subtraction methods. SHM enables a shift in structural maintenance from schedule-driven to condition-based which potentially leads to considerable cost and time savings.

Guided Wave SHM is gaining popularity as a prominent candidate for many applications.[1, 3, 5] Guided waves are constrained by the boundaries of the structure and can travel long distances without significant attenuation, hence offering good area coverage with sparse sensor arrays.[6] It was shown that characterisation of guided wave propagation in the structure or material is of huge importance in order to determine the most suitable wave modes and operational frequencies for a particular application before a reliable SHM system based on guided waves can be deployed.[7] Moreover, structures are usually exposed to varying environmental conditions and their effects on the recorded signals must be understood and quantified in order to be able to distinguish between damage and environmental changes. Temperature variations have been shown to have a huge impact on the guided wave propagation and various compensation strategies have been developed to account for this.[8, 9, 10] However, a full integration of those methods into the SHM processes has not been achieved yet because of complexity, data and time requirements. The following sections will describe several problems with current temperature compensation strategies, highlighting the necessity of their incorporation into SHM processes and propose a novel algorithm to address these issues.

1.1 Temperature Effect

Structures are usually subject to varying and uncontrolled environmental conditions such as temperature, boundary condition, loading and other changes.[11] Most of the structures experience temperature variations...
and it was shown to have a huge impact on guided wave signals[9, 8]. The primary effect of temperature change is the time shift of guided wave signals while the secondary effect is the distortion of the shape of the signal.[12] The time shift, $\delta t$, of a signal can be expressed in terms of temperature change, $\delta T$, as:[8]

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

where $d$ is the propagation distance, $v$ is the phase velocity of the guided wave mode at the centre frequency, $\alpha$ is a thermal expansion coefficient of the material and the $k$ is the coefficient that represents velocity change of the wave mode with respect to temperature. As have been mentioned earlier, SHM system observes only the relative changes in the system – the measured signal, $I_1(t)$ is subtracted from the baseline signal, $I_0(t)$, signal that has been obtained previously when the structure was in a 'healthy' state. The maximum value in this resulting residual signal purely due to temperature effect can be expressed as:[3]

$$|u_{res}(t)|_{max} = |I_1(t) - I_0(t)|_{max} = u_0 \omega \frac{d}{v} \left( \alpha - \frac{k}{v} \right) \delta T$$

where $u_0$ is the amplitude and $\omega$ is the angular frequency of the guided wave signal. Generally, it is desirable to suppress the temperature effect to $|u_{res}(t)|_{max} / u_0 < -30db$ as signal in the residual signal corresponding to the damage is expected to be on $\sim -20dB$ level.[9] Therefore, the compensation for the temperature effect is critical in order to maintain good sensitivity to damage.

### 1.2 Temperature Compensation Methods

The most widely known temperature compensation methods are Optimal Baseline Subtraction (OBS) and Optimal Stretch Method (OSM).[9, 13, 10] In OBS a set of baseline signals that cover the range of operational conditions is used instead of a single baseline. A baseline signal that gives the best subtraction with a measured signal is selected from the set. The selection criterion can be a minimum of maximum of the residual signal, a minimum of rms of the residual signal or other.[10]. The OSM procedure involves a single baseline being stretched/compressed to best match the recorded signal. However, OSM alone is not able to suppress the temperature effect to the desired level even at relatively small temperature changes ($< 10^{6}C$).[9] Therefore, a combination of OBS and OSM procedures is usually used to compensate for temperature variations – a baseline giving best subtraction is first selected from the set and then stretched/compressed to match the recorded signal. There are other variations of these methods such as the use of two weighted baselines instead of a single for OSM.[10]

### 1.3 The Problem of Baseline Set Acquisition

As is clear from the previous section, a set of baseline signals that cover the range of operational conditions of the structure must be obtained. This is done by creating a set from the measurements made on the structure prior to the start of the monitoring phase of the SHM process. Moreover, there is usually no control or knowledge of temperature variations during baseline measurements and all of the measurements are added to the baseline set. There are several disadvantages to such a procedure:

- an assumption that the structure is damage free during the acquisition of baseline set has to be made;
- if there is no control over temperature it is hard and sometimes impossible to cover the whole operational temperature range of the structure;
- if there is no knowledge of temperature during the acquisitions the set might have many baselines that correspond to the same/similar temperature;
- if the operational temperature range of the structure is unknown beforehand a complete set could not be achieved and might compromise the reliability of temperature compensation methods and in turn the whole SHM process;
an assumption that there would be no structural changes that are not associated with damage during the lifecycle of the structure has to be made.[14] Therefore, to attempt to mitigate some of those issues a novel and efficient algorithm for the acquisition of the baseline set is introduced in the subsequent sections. It addresses the problem of the set completeness by making the baseline acquisition an evolutionary process, which is incorporated into the SHM procedure itself. The results on the test of the algorithm on experimental data are presented and future steps required for full integration of the algorithm into the SHM system are discussed.

2 Baseline Set Acquisition Algorithm

A schematic diagram of a proposed algorithm for baseline set acquisition is presented in figure 1. A single measurement on the structure has to be made beforehand so that the initial baseline set can be created. Every other subsequent measurement is temperature compensated using OBS and OSM procedures and then depending on how well it is suppressed the decision is made on whether the measurement should be added to the baseline set. The criterion for decision was chosen to be the maximum value in the residual signal. If it is higher than $-30$ dB, the signal is added to the baseline set. This threshold value is dependent on the damage type the SHM system is designed to detect. The algorithm guarantees that the signals in the baseline set are well spaced in temperature domain because of the maximum residual level and temperature change relation described by equation 2.

![Diagram of Baseline Set Acquisition Algorithm]

Figure 1: A schematic diagram of the proposed algorithm for baseline set acquisition.

However, increased levels in the residual signal might not necessarily correspond to temperature variation,
it might also be due to the initiation of the damage in the structure. Therefore, it is necessary to be able to differentiate between damage appearance and temperature variations in order to integrate the baseline acquisition into the SHM process. Two parameters have been introduced for this purpose:

- Localization parameter. A Rayleigh maximum likelihood estimate (RMLE) together with a sum and delay imaging algorithm was used to construct SHM images combining the information from different sensors in the sensor network.[15] In the case of damage initiation, the reflection/scattering signals should be observed in the residual signals and they should be localized in space corresponding to the damage position. On the other hand, temperature change should induce a more uniform response in the residual signals and therefore poor localization would result in the image. The localization parameter is calculated by taking the ratio of the maximum value and mean value of the image.

- Baseline set growth parameter. The number of baselines in the set with respect to time is recorded during the SHM process. It is expected that the baseline set would grow rapidly in the beginning and slow down after a while when the structure has been exposed to most of its operational temperature range. If the damage is initiated at the time when the set growth has slowed down, it can be projected that the set growth will increase again as the structure with damage would be effectively a different structure that needs a new set of baselines.

It is worth mentioning that the second parameter can be used as a damage indicator only when the set growth has reached the plateau phase. During the processing of each guided wave SHM measurement made on the structure, these two parameters are calculated and the user is informed of any damage indications. This algorithm was implemented in Matlab 7.10.0.

3 Experimental Setup

The schematic diagram of the experimental instrumentation, which can be regarded as a prototype for a guided wave SHM system, is presented in figure 2. Ultrasonic PZT piezoelectric sensors (20mm x 1mm,
optimized for generating fundamental symmetrical, $S_0$, Lamb wave mode) are used to excite and measure guided wave signals. The sensors are glued to the structure with cyanoacrylate. A signal generator is used to excite sensors with an arbitrary input signal and an oscilloscope is used to measure the responses. Two multiplexers are used to switch between sensors in the network for transmission and reception and obtain all possible combinations of sensor pairs operating in a pitch-catch mode. A 12V chirped input signal, which has a bandwidth equivalent to the one of a 5 cycle hanning windowed toneburst, is used as an excitation signal. It gives a relatively good signal to noise ratio and therefore no pre-amplification is needed for the received signals.

The system was deployed on two different structures:

- A water storage tank (shown in figure 3), which is exposed to real environmental conditions. The tank is made out of 5 steel cylinders that are joined together. It was empty throughout the duration of the experiment. Nine sensors have been glued on the tank. A 5 cycle Hanning windowed toneburst with a centre frequency of 250 kHz has been used as a transmission signal. The group velocity of $S_0$ Lamb wave mode in the structure was estimated to be $\sim 5600\text{m/s}$.

- An aluminium plate. Dimensions of aluminium plate are – 2550mm x 1250mm x 3mm. It had a few holes and a corrosion patch prior to the start of the experiment. A hole of 6mm diameter has been drilled at some point during the experiment to simulate an impact damage. Nine sensors have been glued on the plate. A 5 cycle Hanning windowed toneburst with a centre frequency of 200 kHz has been used as a transmission signal. The group velocity of $S_0$ Lamb wave mode in the plate was estimated to be $5480 \sim \text{m/s}$.

Figure 3: A water storage tank with an ultrasonic sensor network.
4 Results and Discussion

An example of a guided wave signal measured by a sensor pair in the aluminium plate experiment is shown in figure 4 together with the effect of the temperature compensation methods. It can be seen that OSM contributes especially to the suppression of later parts of the signal.

![Graph showing signal and residual signals after OBS and OSM compensation methods.](image)

Figure 4: An example of a measured signal (blue) obtained by a certain sensor pair in the aluminium plate experiment and residual signals after application of OBS (black) and OSM (red) temperature compensation methods. The signals are normalised to the first arrival and compensated for a beam spread effect.

A baseline set acquisition algorithm, described in section 2, was firstly tested in the SHM experiment on the water tank. Figure 5 indicates the growth of the baseline set for some of the sensor pairs over the course of ~ 4 days. By the end of the experiment there were a total number of 125 baselines in the set out of 1680 recorded signals (~ 7%). Therefore, the algorithm leads to a significant reduction of the size of the set without compromising the capabilities of temperature compensation methods. This saves memory space and computational time for temperature compensation algorithms. It is worth observing, that the growth rate of the set has also slowed down at the end of the experiment. In addition, the set size is different for different sensor pairs, which is caused by different complexity of the signals recorded from different locations with respect to the structural features.
Figure 5: Baseline set growth for some of the sensor pairs during SHM experiment on the water tank. The time step between the measurements is 20 minutes.

The algorithm was then tested in the SHM experiment on the aluminium plate to determine its capabilities of distinguishing between damage initiation and temperature variations. Figure 6 shows the baseline set growth and again indicates the efficiency of the algorithm, only ~ 7% of the recorded signals have been added to the baseline set. Figure 7 compares RMLE images of residual signals of a typical damage free case with damaged case. A good localization is achieved in the presence of damage even though the defect size-wavelength ratio is only 0.22. Therefore, it is a promising tool for damage and temperature effect differentiation.

Figure 6: Baseline set growth during the SHM experiment on the plate for different sensor pairs. The time step between the measurements is 20 minutes.
Figure 7: The RMLE images of residual signals: (a) typical image when there is no damage, (b) an image with damage presence (6mm diameter hole). The black dots represent sensor locations and a white circle represents the true location of the damage. Note the difference in the amplitude scales in the images.

Figure 8 shows the performance of the proposed parameters for indirect damage indication. Both of the parameters clearly peak at the point of damage introduction in the plate. However, the localization parameter is less susceptible to temperature changes as can be seen at ~16th hour when the value of baseline set growth parameter is observed well above its average value due to larger temperature change. Therefore, the localization parameter is more indicative of the damage in the presence of huge temperature variations or in the beginning of the SHM process when the baseline set is relatively small.

Figure 8: Set growth (black) and localization (red) parameter values during the SHM experiment on the plate. Set growth parameter is the difference between number of baselines in the set between two subsequent measurements averaged over all sensor pairs. Localization parameter has arbitrary units and is normalized to one in the figure. The highest peaks of the parameters correspond to the time when the hole was introduced in the plate.
5 Conclusions

A novel algorithm has been proposed to address the baseline set acquisition problem for guided wave SHM. The algorithm allows integrating the baseline acquisition into the SHM, which makes the acquisition an evolutionary process that solves the problems outlined in section 1.3. Its efficiency has been proved experimentally. Moreover, two parameters have been introduced to give an indirect damage indication so that the effect of temperature and damage can be differentiated. The parameters were successful in detecting the time of a simulated impact damage initiation. However, it was noted that localization parameter is less affected by temperature variations than baseline growth parameter.

The future work will firstly concentrate on determining experimentally independent thresholds of damage indication for the parameters. This would require quantification of the influence of temperature changes on the parameters. The performance of the parameters is expected to depend largely on such variables as number of sensors in the network, network layout and the overall complexity of the structure. In addition to this, a more sophisticated and reliable peak detection in the RMLE images should be established as well. Finally, an approach to address slowly evolving damage has to be identified so that such damage types as corrosion and fatigue crack growth could be detected as well.

References


