Local Interaction Simulation Approach for Temperature Effect Modelling in Lamb Wave Propagation

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ABSTRACT

The paper explores the ability of numerical simulations for Lamb wave propagation in plates exposed to temperature fluctuations. The local interaction simulation approach is used for wave propagation modelling. The newly developed parallel computation technology - offered by modern Graphics Processing Units (GPUs) and Compute Unified Device Architecture (CUDA) used in low-cost graphical cards – is used in these numerical simulations. This allows for very efficient wave propagation simulation for various temperatures. Numerical simulation results can be used more effectively to develop new signal processing techniques to compensate for temperature effects.

INTRODUCTION

Lamb waves are the most widely used ultrasonic guided waves for damage detection. Many damage techniques have been proposed in recent years, as reviewed in [1-3]. The majority of Lamb wave based approaches rely on usually small changes of amplitude and frequency in Lamb wave responses due to structural damage. However, it is well known that real engineering structures are exposed to fluctuating operational and environmental conditions that can mask these changes due to structural damage. As a result, damage-related features are often embedded in the background noise and are very difficult to interpret.

Lamb wave sensitivity to temperature fluctuation is one of the major problems. In practice it is very important to compensate for this effect [4-5]. Otherwise it is difficult

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to distinguish between changes caused by temperature fluctuations and changes due to damage.

Various methods have been developed to compensate the temperature effect in Lamb wave propagation. The methodology based upon the prediction and observation that the first order effect of temperature change on a diffuse ultrasonic wave is time dilation or compression have been shown in [6]. Two different methods, namely Optimal Baseline Selection (OBS) and Baseline Signal Stretch (BSS), have been described in [7]. In [8] method using redundant signal measurements has been proposed. Reference-free approach has been described in [9]. Advanced signal processing can be also used to classify temperature-effected Lamb wave data [10]. Many of these approaches require expensive experimental tests to obtain reference database for various temperature conditions. This is often expensive and not always possible. It is clear that numerical simulations could significantly ease the temperature compensation process.

Elastic wave propagation modelling using analytical methods is feasible mainly for simple problems. Semi-analytic methods contain approach based on the theory of diffraction [11] and boundary element methods [12]. Numerical algorithms include a number of different approaches. This includes methods based on Finite Elements (FE) [13], finite differences (FD) [14], velocity-stress [15], spectral elements [16] and local interaction simulation approach (LISA) [17-21]. The latter - recently implemented using parallel processing architectures and graphical cards [22-23] - has proven very efficient for wave propagation in complex media with sharp interfaces. The objective of the paper is to explore the capability of this LISA computation platform for temperature effect modelling in Lamb wave propagation.

This paper is organised as follows. In the second section, the LISA approach is briefly described. Then, equivalent validation for numerical simulations and real experiments is introduced. This is followed by numerical simulations that are compared with experimental results. Finally, conclusions and future work proposal are given.

THE LOCAL INTERACTION SIMULATION APPROACH FOR LAMB WAVE PROPAGATION

The Local Interaction Simulation Approach (LISA) technique was proposed original in physics [17-19] for wave propagation in complex media with sharp impedance changes. The LISA algorithm was primarily designed for simulation using parallel processing, to be used mainly on computer with thousands of parallel processors.

The LISA can be used for wave propagation in a heterogeneous material of any shape and complexity. This method discretises the examined structure into a grid of rectangular cells. The material properties are assumed to be constant within each cell but may vary between cells. The algorithm can be derived from the elastodynamic wave equation for homogenous media expressed as [24]

$$(\lambda + \mu)\nabla\nabla \cdot W + \mu\nabla^2 W = \rho W_{,tt} \qquad (1)$$

where 1 and fl are Lamé constants, ρ and W is the material density and the vector of particle displacements with u and v components, respectively. Indices after comma denote differentiating with respect to those quantities in Equation (1).

This equation can be discretised in both time and space, giving the general form

$$D^{t+1} = f(D^{t-1}, D^{t}) \tag{2}$$

f is a general function of field variables; D is the field quantity vector (i.e. displacement, velocity and acceleration) and t is a given time step. Equation (2) shows that in every next time step, values of the field quantity vector are calculated as a linear combination of the same field variable vector from the previous time steps, allowing for parallel processing.

The LISA algorithm has been implemented in MATLAB using Graphical Processing Units (GPUs) and the Compute Unified Device Architecture (CUDA) technology. Previous studies have demonstrated significant reductions in computation time by a factor of up to 1000 [22-23] when low-cost graphical cards - available in modern PCs - have been used.

EQUIVALENT VALIDATION

Performing numerical simulations before conducting laboratory experiments is very common and useful nowadays. Practically experiments are not carried out without prior numerical analysis. Simulation results allow one to predict the results of the system response, thereby preventing the multiple repetition of unnecessary tests.

The results of numerical simulations can be used to develop new methods of temperature compensation for Lamb waves propagation. Currently, the temperature effects and other environmental factors influencing the wave propagation is one of the major problems associated with the implementation of Lamb for real engineering applications. Simulations performed by means of commercially available software (e.g. ANSYS or MARC) are time consuming due to high frequeny and high-velocity waves investigated. In commonly used FE software packages, high resolution models and small steps need to be used. This produces very long calculation times.

In this paper cuLISA3D software [22-23] was used for numerical simulations. This allows for rapid calculations not only of simple models but also of very complex and large configurations.

NUMERICAL SIMULATION AND EXPERIMENTAL TESTS

In order to obtain Lamb wave responses for various temperatures, numerical simulations were performed using the cuLISA3D software. These results were compared with experimental data obtained in the experiment fully described in [10]. Lamb wave propagation in a rectangular (200 x 150 x 2 mm) aluminum plate was modelled. Two piezoelectric transducers (diameter 10 mm) were bonded to the plate in a symmetrical configuration.

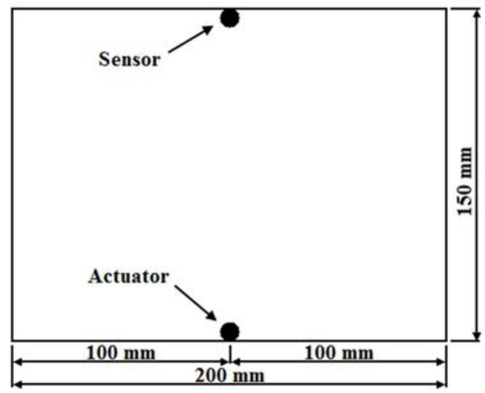

Figure 1. Aluminum specimen with sensor and actuator locations.

Figure 1 shows the geometry of the undamaged panel and sensors locations used in numerical simulations and in experimental tests. A five-cycle cosine burst signal was used as an excitation. The input signal was enveloped using a half-cosine window. The excitation frequency was equal to 75 kHz. The maximum peak-to-peak amplitude of the excitation signal was equal to 10 V. Figure 2 shows the excitation signals used in numerical simulations and experimental tests.

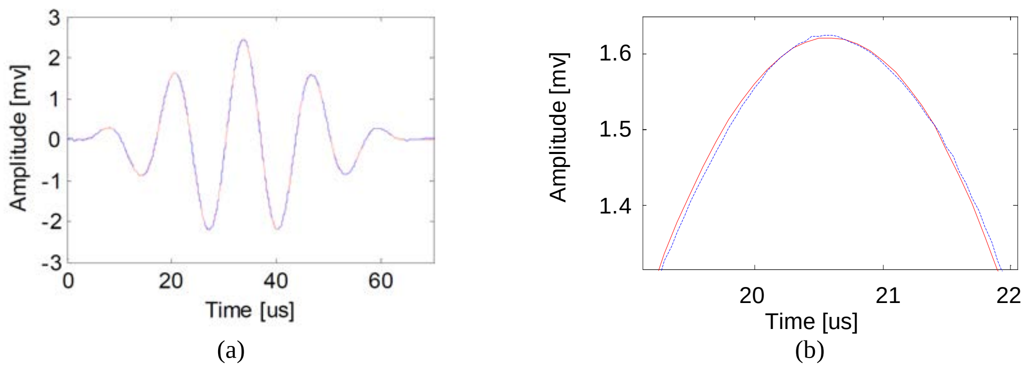

Figure 2. Excitation signal (a) and its zoomed fragment (b) used for Lamb wave propagation. Dashed waveforms correspond to numerical simulations whereas solid waveforms represent experimental data.

Numerical simulations were performed for the temperature values equal to 30, 40, 50, 60 and 70^{0}C. Temperature-dependent physical properties and wave propagation parameters were used in these investigations; any material expansion due to temperature was neglected.

Figure 3 gives an example of two normalised Lamb wave responses obtained for the minimum and maximum temperatures investigated. The results obtained from numerical simulations were compared with experimental data. The first wave packet in these Lamb wave responses is the A0 mode. The following wave packets were identified as reflections from the boundaries. The results in Figures 3a and 3b show that Lamb wave responses are different when the temperature is changed from 30 to 70^{0}C, as expected. Relatively good agreement between simulated and experimental data can be observed.

Two Lamb wave parameters, namely the arrival time of the first wave package and the peak-to-peak amplitude, were further investigated for all temperature values. The former was calculated using thresholding. The results for the simulated and experimental data are given in Figures 4. These results show that the arrival time increases whereas the amplitude decreases with the temperature, as expected. A relatively good agreement between the simulated and experimental data has been achieved for the arrival time when the temperature range from 30 to 60^{0}C in Figure 4a. However, the experimental arrival time value for the 70^{0}C temperature is slightly lower if compared with the simulated values.

The peak-to-peak amplitude exhibit good agreement between the simulated and experimental data for the temperature range from 30 to 50^{0}C in Figure 4b. The experimental results for the remaining temperature values are lower than for the simulated data.

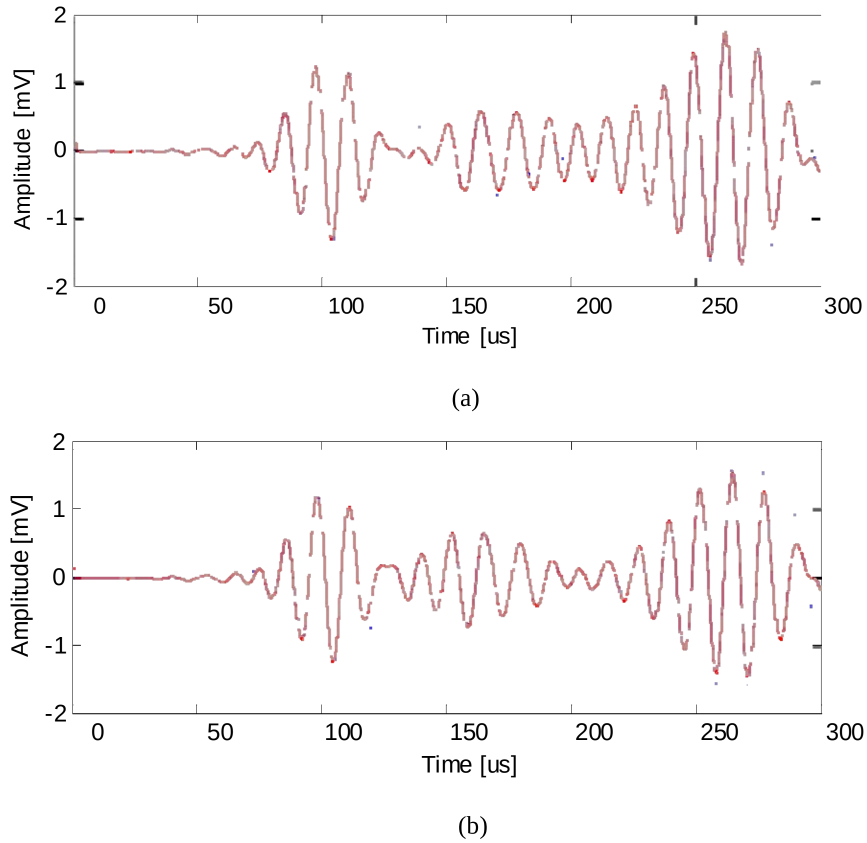

Figure 3. Lamb wave responses for: (a) temperature 30°C; (b) temperature 70°C. Dashed waveforms correspond to numerical simulations whereas solid waveforms represent experimental data.

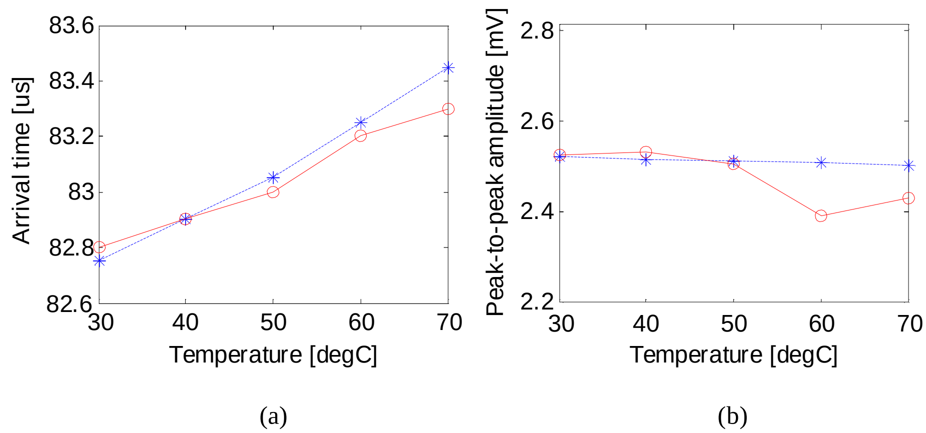

Figure 4. Temperature effect results: (a) arrival time vs. temperatures; (b) peak-to- peak amplitude values vs. temperatures. Dashed lines correspond to numerical simulations whereas solid lines represent experimental data.

CONCLUSIONS

The LISA algorithm based on parallel processing - and implemented using GPUs and CUDA - have been used for Lamb wave propagation modelling. The major task was to explore the method for temperature effect simulations.

The simulation results demonstrate relatively good accuracy when compared with the experimental data. Some discrepancies observed for larger temperature values need further investigations. Nevertheless these exploratory results show that the developed computation platform could be useful for temperature effect modelling.

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