The influence of global and local temperature variation on elastic guided wave excitation, propagation and scattering

J. Moll\textsuperscript{1}, A.A. Eremin\textsuperscript{2,3} and M.V. Golub\textsuperscript{2}

\textsuperscript{1} Department of Physics, Goethe University of Frankfurt am Main, Frankfurt am Main, Germany, E-Mail: moll@physik.uni-frankfurt.de
\textsuperscript{2} Institute for Mathematics, Mechanics and Informatics, Kuban State University Krasnodar, Russia, E-Mail: m_golub@inbox.ru and eremin_a_87@mail.ru
\textsuperscript{3} Institute of Mechanics, Helmut Schmidt University, Hamburg, Germany

Abstract

In this paper, the global and local temperature effects are considered and their influence on ultrasonic guided waves (GW) excitation, propagation and scattering are investigated numerically and experimentally for metallic and polymer plate-like specimens. Computer simulation of the phenomena relies on semi-analytical and mesh-based approaches as well as on recently developed hybrid schemes combining both approaches.

Firstly, global temperature effects are addressed by fitting data from pitch-catch experiments in the environmental chamber and the implemented mathematical model. This allows the estimation of temperature dependent material properties by solving an inverse problem. Secondly, local temperature changes occurring near surface mounted low-profile piezoelectric actuator after its prolonged continuous ultrasound excitation. Such local heating is visualized with an infrared camera. The influence of the obtained non-neglectable heating on actuator GW generation and sensing capabilities is illustrated. In addition, local temperature increases at the damaged areas (flat-bottom holes (FBHs) are considered as the defects) being a result of acoustic activation. This effect is shown in pitch-catch signals acquired by the sensor network surrounding the obstacle location. While temperature effects are usually unwanted in structural health monitoring (SHM) systems, this observation may lead to a novel type of contrast mechanism for ultrasound-based damage detection in SHM systems.

1. Introduction

Ultrasonic guided waves (GW) are widely employed in structural health monitoring (SHM) systems due to the relative ease of their activation and measuring and the ability to interrogate prolonged thin-walled constructions with a distributed actuator-sensor network. Along with the structural mechanical properties and geometry features, environmental conditions influence strongly GW dynamic characteristics, with temperature effects being among the most important ones. The latter might have the \textit{global} nature, when the whole inspected object is exposed to ambient temperature fluctuations (cooling or heating), or be of \textit{local} nature near structure peculiarities, such as operating piezoelectric actuators utilized for GW excitation or temperature increase at the defect in response to acoustic activation. Temperature variation results in changes
in GW amplitudes and dispersion properties and, therefore, should be properly addressed for the reliable operation of GW-based SHM systems.

In the literature, the global temperature effects have been well studied. Algorithms for compensation of the temperature effect have been widely employed which are based on Optimal Baseline Selection (OBS) and/or Baseline Signal Stretch (BSS) [1]. The baseline stretch approach has been extended to larger temperature gaps for instance in [2]. Other temperature compensation methods are based on the independent component analysis (ICA) [3] and singular value decomposition (SVD) [4].

Local temperature effects at a structural defect are widely used in the context of non-destructive testing (NDT). One possible approach is pulsed thermography where thermal energy is delivered to the sample of interest by an external source such as infrared lamps or flash lamps [5]. Images recorded by a thermal camera indicate the damage position and size. Vibrothermography, on the other hand, uses either a mechanical shaker [5] or a high power narrowband ultrasound stimulation [6], [7] that initiates heating in the defect either by Coulomb friction or damping/internal friction [8]. The temperature increase can be visualized by a thermal camera system. A combination of wideband ultrasound excitation and local defect resonances have been studied in [10] where the locally induced temperature increase is visualized by a sensitive IR camera. An overview of thermographic methods for condition monitoring applications can be found in [9].

The goal of the present paper is to investigate both, the global as well as the local temperature effect. Therefore, Section 2 focuses on the global temperature effect, particularly on the temperature-dependent Young’s modulus. Section 3 analyses the local temperature increase at the defect as a result of acoustic activation. Finally, conclusions are drawn at the end.

2. Assessment of global temperature effects

2.1 Experimental setup for temperature-controlled pitch-catch measurements

Figure 1. Design (a) and photo (b) of the specimen
The experimental setup used in this study is based on an isotropic plate on which three piezoelectric wafer active sensors (PWAS) are attached to the surface as shown in Figure 1. The structure has been put in a climate chamber to perform controlled temperature experiments. A Hann-windowed toneburst voltage signal with central frequency $f_0$ kHz is employed and the guided wave response is sensed at the two receiver positions that have a distance to the actuator of 50mm and 160mm, respectively (see Figure 1).

![Figure 1. The experimental setup used in this study](image)

![Figure 2. Hilbert transforms of the signals acquired by Sensor 2 at different temperatures](image)

Measurements have been repeated at different temperatures $T$ in the climate chamber. Figure 2 demonstrates the Hilbert transform applied to the signals $u_1(t)$ and $u_2(t)$ recorded by the Sensors 1 and 2 for temperatures $T$ from 0°C to 51°C at central frequencies of 40kHz and 240kHz. The antisymmetric wave mode $A_0$ is the dominant wave mode at lower frequencies, while the symmetric mode $S_0$ is clearly seen at higher frequencies. The increase of temperature causes decrease of the amplitudes excited by the actuator and increase of the time-of-flight of wave package generated. The latter is in a good agreement with results obtained in [11]. However further analysis is necessary for the understanding of the influence of the temperature on Lamb wave propagation.

### 2.2 Group velocity estimation by means of wavelet transform

Time-frequency analysis is applied to the signals $u_1(t)$ and $u_2(t)$ correspondingly. The continuous wavelet transform (CWT)

$$ W[u](f,t) = \left| \frac{\sqrt{f}}{f_0} \int_{-\infty}^{\infty} u(\xi - t) \psi_{f_0} \left( \frac{\xi - t}{f_0} \right) d\xi \right| $$

(1)
gives the spectrum of a signal \( u(\xi) \) recorded during the period of time \( \xi \in [t_1, t_2] \). The CWT is implemented in terms of the kernel wavelet function \( \psi_{\text{G}}(t) \) and the central frequency \( f_0 \) of the input voltage signal applied to the Actuator. The Gabor wavelet
\[
\psi_{\text{G}}(t) = \pi^{0.25} (f_0 / \gamma)^{0.5} \exp\left(-0.5(f_0 t / \gamma)^2 + i f_0 t\right)
\]
with the parameter \( \gamma = \pi \sqrt{2 / \ln 2} \approx 5.336 \) is selected as a kernel function for CWT due to its correspondence to the generated signal [12].

The CWT of a signal can be calculated at an arbitrary moment of time within the time-domain considered. Correspondingly, the time-of-flight \( a \) of a given frequency \( f \) in the signal is defined as a maximum of the absolute value of the CWT (1), i.e.:
\[
a(f) = \max_{t \in [b_1, b_2]} |W[u](f, t)|.
\]

The interval \( t \in [b_1, b_2] \) defines the part of the signal to be interpreted using the CWT, the latter can be used in order to separate different Lamb waves. Thus, the time-of-flight \( a_j(f) \) of the frequencies \( f \) can be performed for the signals \( u_j(t) \) measured by \( j \)-th Sensor \( ( j = 1, 2 ) \). Due to the distance \( D = 110 \text{ mm} \) between the centres of Sensor 1 and Sensor 2 is known the group velocities of Lamb waves can be estimated as follows:
\[
c_g(f) = \frac{D}{a_2(f) - a_1(f)}.
\]

The values of \( a_j(f) \) are calculated using the relation (2) for each Lamb wave separately via the appropriate choice of the time-domain interval \( t \in [b_1, b_2] \).

2.3 Temperature influence on group velocity of antisymmetric Lamb wave A0

![Graph showing group velocity vs frequency for different temperatures and theoretical predictions.](image)
Figure 3. Group velocity variation with temperature increase (measured) and with Young’s modulus increase (theoretically predicted)

The experimental setup described in (2.1) was used to record the wave motion at sensors 1 and 2. The latter are processed via the CWT so that the frequency dependence of the group velocity \( c_g(f) \) is estimated at different temperatures in accordance with formulae (3). An example of group velocity variation for A0 mode at different temperatures is demonstrated in Figure 3, the estimated velocities are shown by solid lines. Analysis of the obtained data shows that group velocity increases with temperature decrease.

Let us consider group velocities of an elastic plate with Poisson ratio \( \nu \), Young’s modulus \( E \) and density \( \rho \) have been examined. In order to examine the influence of the temperature on elastic properties of the plate, it has been assumed that aluminium plate has the same Poisson ratio \( \nu = 0.34 \) and density \( \rho = 2700 \text{ kg/m}^3 \) for arbitrary temperature \( T \). The theoretically predicted group velocities of A0 mode are shown in Figure 3 by dashed lines. The performed analysis of the obtained data allows concluding that temperature effects can be taken into account during simulations via a corresponding change of the elastic moduli. However, the obtained data is not enough for careful estimating of the values of the Young’s modulus \( E \), further studies with circular shaped piezoelectric transducers are to be done for this purpose using the technique presented above.

3. Assessment of local temperature effects

The work presented in the following section is based on very preliminary studies for temperature increase at the defect in response to acoustic activation. Further work is needed to better understand the underlying mechanisms. While preparing the experimental setup, we have first observed that a temperature increase by acoustic activation cannot be achieved for metal structures due to the better thermal conductivity which leads to a quick temperature balance in the structure. This is the reason for choosing a plexiglass plate in this work, in which thermal conductivity is reduced. Moreover, high power acoustic activation may also lead to melting of the plastic structure due to strong temperature increase at the exciting piezoelectric transducer, especially at high output power and high frequencies.

3.1 Experimental setup for temperature-controlled pitch-catch measurements

Figure 4 depicts the experimental setup for analysing local temperature increase at the defect. A plexiglass plate of dimensions 500×500×2 mm³ is serving as specimen. It is equipped with six small circular PWAS adhesively attached in the vertexes of a regular hexagon, circumscribed around a circle of radius 100 mm centered at the plate mid-point. The experiment had several phases: In the first phase, all actuator-sensor combinations using the multiplexer proposed in Ref. (1)

free structure at frequencies up to 300kHz. This measurement serves as the baseline measurement. In a next step, a circular FBH of radius \( r = 1.8 \) mm and depth \( d = 1.55 \) mm has been introduced on the ray passing between the second \( T_2 \) and the third \( T_3 \) sensor 60 mm away from the plate centre, and measurements have been taken without and with acoustic activation using the rectangular block transducer \( T_A \) adhered on the same path at the 120 mm off-centre location.

![Experimental setup for analysing local temperature increase at the defect.](image)

Figure 4. Experimental setup for analysing local temperature increase at the defect. A rectangular block transducer \( (T_A) \) is used for acoustic stimulation. Six circular transducers \( (T_1-T_6) \) are positioned around the plate centre to measure all actuator-sensor combinations in a round-robin fashion. Signal generation is performed by a Handyscope HS3 arbitrary waveform generator. A thermal camera takes snapshots of the temperature distribution in the plate.

To determine the frequency, on which \( T_A \) should be excited to achieve the temperature increase at the obstacle, GWs have been measured at the FBH with a scanning lased Doppler vibrometer Polytec PSV-500 after the broadband 1\( \mu \)s rectangular pulse excitation with \( T_A \). The acquired out-of-plane velocities \( v_3 \) at the mid-point of the defect and the corresponding spectrum are summarized in Figure 5. Several clear local maxima are visible, e.g., at \( f_1 = 96.5 \) kHz and \( f_2 = 176.5 \) kHz. Since the heating in plexiglass is expected mainly due to high oscillation amplitudes, further the acoustic activation is based on a harmonic sinusoidal excitation at 96.5kHz at 50Vpp.
Figure 5. Transient out-of-plane velocities $v_3$ (left) measured at the centre of the FBH after the broadband excitation of $T_A$; spectrum of this signal (right, blue line); red line corresponds to the spectrum of the signal $v_3(t > 0.1 \text{ ms})$ (the results are scaled for the consistency).

3.2 Results of local temperature increase

The first result is shown in Figure 6 in form of a thermal image showing the local temperature increase at the defect during acoustic activation. The temperature increase at the defect is approximately 0.3K which can be clearly discriminated from the homogeneous surrounding domain.

Figure 6. Snapshot of the thermal camera showing the local temperature increase at the flat bottom hole (FBH), the strong heating of the stimulation block transducer $T_A$ as well as the slight temperature increase at the adjacent transducer due to electromagnetic coupling.

Figure 7 shows the frequency spectra and time-domain data of the unfiltered and filtered signals. Since the measurement has been conducted during parallel acoustic activation, the strong 96.5kHz signal had to be filtered. This filtering has been conducted for all measured signals to achieve a consistent result.
In a next step, ultrasound signals shall be compared for three different cases: (1) undamaged structure (2) structure with damage, i.e. a FBH, (3) structure with damage plus acoustic activation. The results are shown in Figure 7 and Figure 8 for two different actuator-sensor paths, namely $T_1-R_3$ (FBH on direct path) and $T_4-R_6$. It is important to note that a temperature sensor has been placed below the flat bottom hole where temperature differences <0.2K have been measured between subsequent measurements.

It can be clearly observed that a signal change can be measured between measurements from the undamaged and the damaged structure (conventional approach). Interestingly, a significant signal change can also be found for the case when the damaged structure is compared with the damaged structure plus acoustic activation. Two ultrasound measurements are shown here to demonstrate consistency of the measurements. Differential signals are plotted on the bottom parts of Figure 8 and Figure 9 to illustrate signal differences.
Figure 8. Transducer pair T1-R3 at 300kHz: (Top left) Raw signals for the pristine structure, two measurements for the structure with the flat bottom hole (FBH) and two measurements with the FBH plus acoustic activation. (Top right) Zoom of the raw signals plot showing a change in time-of-flight. (bottom) Differential signals showing a residual after subtraction.

3.3 Discussion of temperature elevation at the defect at off-resonance frequencies

Along with the temperature increase itself it is interesting to reveal the nature of local peaks observed in the frequency response curve for the point inside the FBH shown in Figure 5. For a severe damage of this type their location in frequency domain is typically associated with resonance frequencies of the considered GW diffraction problem [13]. At such frequencies the incoming GWs not only interact with the obstacle through scattering but also initiate high-amplitude prolonged motion at its vicinity.
To check whether this phenomenon explains local maxima in out-of-plane velocity spectrum curve in Figure 5, theoretical complex eigenfrequencies of the FBH have been at first evaluated with finite element method (FEM) employing COMSOL 5.3 software as it is described in [14]. The following values for the first two resonance frequencies have been obtained: 

\[ f_{1,FEM} = 84.12 - 6.19i \text{ kHz} \]  
\[ f_{2,FEM} = 164.02 - 19.85i \text{ kHz} \]

It is observed that the values of their real parts differ from the corresponding frequencies \( f_1 \) and \( f_2 \). Moreover, due to high values of imaginary part amplitudes the corresponding resonance motion could be only slightly pronounced. Nevertheless, the first experimental eigenfrequency \( f_{1,exp} = 83 \text{ kHz} \) is clearly identified in the spectrum of the signal from Figure 5 (red line, scaled), if the Fourier transform is applied only to the signal part, measured after the incoming wave package left the obstacle area, i.e. for \( t > 0.1 \text{ ms} \), and its value is very close to the predicted one \( f_{1,FEM} \).

Therefore, it might be decided that the introduced FBH is not severe enough to make resonance diffraction being the only source of high amplitude motion at the obstacle. In our case local peaks in frequency response occur probably due to the peculiarities of the FBH-PWAS\( T_A \) mutual location and could be interpreted by the in-phase summation of the incoming and reflected GWs at some certain frequencies. The preliminary 3D FEM-based simulations confirm this guess. While the increase of FBH depth strengthens the influence of resonance localization (Figure 10, top right subplot, where \( v_3(f) \) curves evaluated at the obstacle mid-points for various FBH depths are shown), even slight changes in the distance between PWAS \( T_A \) and FBH result in considerable shift of local peaks in the frequency domain (Figure 10, bottom-right subplot).
4. Conclusions

This work focussed on global and local temperature effects of guided wave propagation in intelligent structures. It was found that a global temperature increase is based on temperature-related changes of the Young’s modulus which has an effect on the dispersion properties. Results are presented here by means of the continuous wavelet transform (CWT). In addition, it was found that a local temperature increase can be measured at the defect as a response to acoustic activation. The latter observation may lead to novel contrast mechanisms in guided wave structural health monitoring (SHM) systems to generate a unique scattering response that can be used for defect imaging. Finally, local temperature elevation has been studied at resonance and off-resonance frequencies with the result that off-resonance frequencies could also provide optimum temperature increase at the considered flat bottom hole.

Acknowledgements

J. Moll gratefully acknowledges the support of this research by the Federal Ministry for Economic Affairs and Energy (grant number: 03SX422B). A.A. Eremin gratefully acknowledges the Alexander von Humboldt Research Foundation for its support to undertake research in Germany via a Humboldt Research Fellowship for Postdoctoral Researchers. M.V. Golub gratefully acknowledges the Russian Foundation for Basic Research and the Krasnodar Region Administration (Project 16-41-230352). The authors express their deep gratitude to Prof. Rolf Lammering (Institute of Mechanics, Helmut Schmidt University) for the comprehensive support of the laser vibrometry and thermography experimental investigations.
References and footnotes


