Ultrasonic Guided Wave Dispersive Characteristics in Composite Structures Under Variable Temperature and Operational Conditions

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ABSTRACT

The well-known properties of guided ultrasonic waves have led to a burst of studies using Lamb waves for detection and analysis of defects in composite structures. However, for reliable health monitoring, much information regarding the innate characteristics of the sources and their propagation is essential. On the one hand, the knowledge of factors like attenuation, wave velocity and energy focusing of Lamb waves allow the optimization of sensor networks in terms of number of sensors and sensor placement, increased source location accuracy and to get an insight into the source mechanisms. On the other hand, there is a need to better understand and deal with the influence of changing environmental and operational conditions which causes changes in the stiffness and damping of the structure and consequently modifies its dynamic behaviour.

On that account, this paper first presents a higher order plate theory applicable for modelling dispersive solutions in elastic and viscoelastic fibre-reinforced composites in order to investigate both the frequency and angular dependency of radiation and attenuation of Lamb waves in anisotropic media. Second, the effects of temperature and surface wetting changes on the response of ultrasonic guided waves are studied in composites. Theoretical developments, numerical and experimental results are presented here in order to analyze the effects of all the aforementioned sources of variability on wave propagation velocities, directionality and attenuation, and bring their significance into focus for the proper development of robust structural health monitoring systems and damage detection algorithms.

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INTRODUCTION

Changing environmental and operational conditions, e.g. temperature, boundary conditions and loads, augment the complexity for the reliable monitoring of a structure. It is well known that temperature as well as damage can have similar effects on the dynamic behaviour of a structure. As a result, dynamic responses obtained either from vibration-based or wave propagation based methods can be affected by these effects and lead to false alarms or wrong damage locations. Therefore, it is very important to understand the impact of these changing conditions and take them into account. Fritzen et al. [1] modified an existing subspace-based identification method with temperature compensation for damage diagnosis. Moll et al. [2] studied the compensation of environmental influences using a simulation model and a laboratory structure. Raghavan and Cesnik [3] reported studies for the selection of suitable bonding agent and identified thermally sensitive variables in experiments to model the experimentally observed changes under temperature variation. Lu and Michaels [4] performed studies in order to find selective features which are sensitive to damage but insensitive to the applied surface wetting. Croxford et al. [5] evaluated two different methods to compensate for the temperature effect, namely optimal baseline selection (OBS) and baseline signal stretch (BSS). Kraemer et al. [6] proposed an approach based on Artificial Neural Networks (ANN) using Self Organizing Maps (SOM) in order to compensate the temperature effects on different features obtained from measured time data of a Carbon Fiber Reinforced Polymer plate (CFRP). Other notable work in the field is given in [7-8]. The majority of the previous studies have been accomplished in isotropic materials. This contribution presents theoretical developments, numerical and experimental results on the effects of variable temperature and operation conditions (EOC) on wave propagation in composite materials. Increase in time-of-flight, effects of surface wetting and changes in sensor response magnitude with temperature are analyzed and discussed.

MATHEMATICAL FRAMEWORK

The model considers a linear viscoelastic, non-piezoelectric layer of material subjected to a complex stress system in three dimensions [9]. The approximated displacement fields are given by

$$\begin{aligned} u &= u_0(x,y,t) + z\psi_x(x,y,t) + z^2\phi_x(x,y,t) + z^3\lambda_x(x,y,t) \\ v &= v_0(x,y,t) + z\psi_y(x,y,t) + z^2\phi_y(x,y,t) + z^3\lambda_y(x,y,t) \\ w &= w_0(x,y,t) + z\psi_z(x,y,t) + z^2\phi_z(x,y,t) \end{aligned} \tag{1}$$

where u, v, and w are the displacement components in x, y and z directions, ψ_x and ψ_y represent rotations having the same meaning as in the first order shear deformation theory [10]. The equations of motion may be derived from the dynamic version of the principle of virtual displacements. Viscoelastic layers can be simulated by allowing the stiffness matrix to be complex. With the proposed method it is easy to obtain the approximate solutions in analytical forms since only polynomial equations need to be solved. Figure 1 shows the velocity curves for the fundamental modes of propagation for a 1.5*mm* unidirectional thick glass fibre reinforced plastic (GRFP) plate at f =60*kHz*. The nominal material parameters are E_1=31*GPa*, E_2=15*GPa*,

E_3=10*GPa*, G_{12}=4.9*GPa*, G_{13}=3.1*GPa* and G_{23}=2.7*GPa*. The density is about 1700*kg/*m^3 and fibre orientation is at 90°. Curves depicted in dots are calculated using exact three dimensional theory and solid lines using the proposed third order plate theory. The curves were calculated using a general-purpose computer program developed by the authors [11]. A satisfactory agreement between the theories is demonstrated.

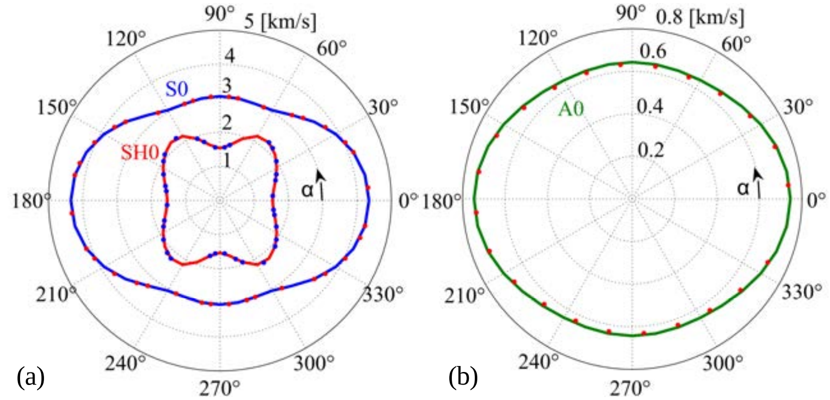

Figure 1. Comparison between the exact 3D solution and the third order plate theory: (a) Phase Velocity for S_0 and SH_0 and (b) Phase Velocity for A_0.

For a frequency up to 800*kHz*, corresponding to a frequency-thickness product of 1.2*MHzmm*, the error in comparison to the group velocity of the S_0-mode is below 3%. Just as good is the conformity of the out-of-plane mode A_0-mode. A viscoelastic carbon fibre reinforced plastic plate with unidirectional fabric reinforcement is analyzed below. The plate has a thickness of 5.1*mm*, density of 1500*kg*/*m^3* and stacking of $[0°]_{18}$. Further details about the plate are given in [12].

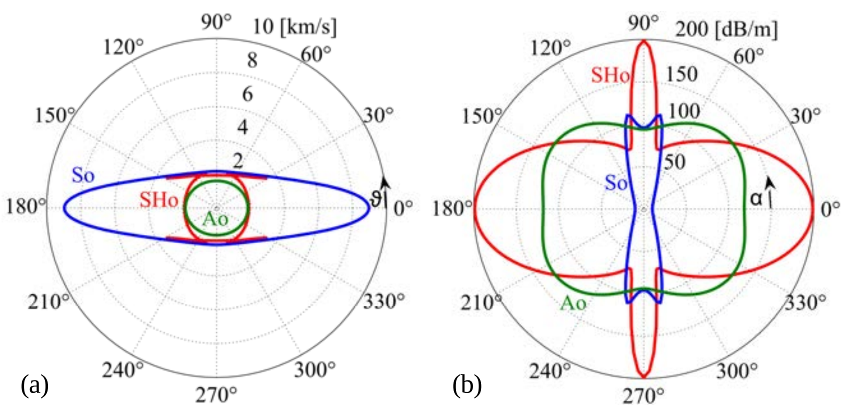

Figure 2. Angle Dependency: (a)Energy Velocities and (b)Attenuation Curves at f=150kHz.

Numerical simulations in Figure 2 demonstrate that material anisotropy has a strong influence on the velocities and attenuation for the modes of propagation, and that they are frequency and angle dependent.

MATERIAL PROPERTIES SENSITIVITY ANALYSIS

Several studies regarding the effects of temperature variability on the measured dynamic responses of structures have shown that temperature variation may change the material properties of a structure [3, 7]. Additionally, factors such as material age effect, moisture content and structure operation affect significantly the wave propagation characteristics in the material. The proposed model is used here in order to study the sensitivity of the energy velocities to the material properties for the GFRP plate presented in the previous section. Figure 3 presents the results for a reduction of 25% for each constant independently at a constant frequency of 60*kHz* for the fundamental modes of propagation. Solid lines represent the results for the original values and the dashed lines the results for the reduced values.

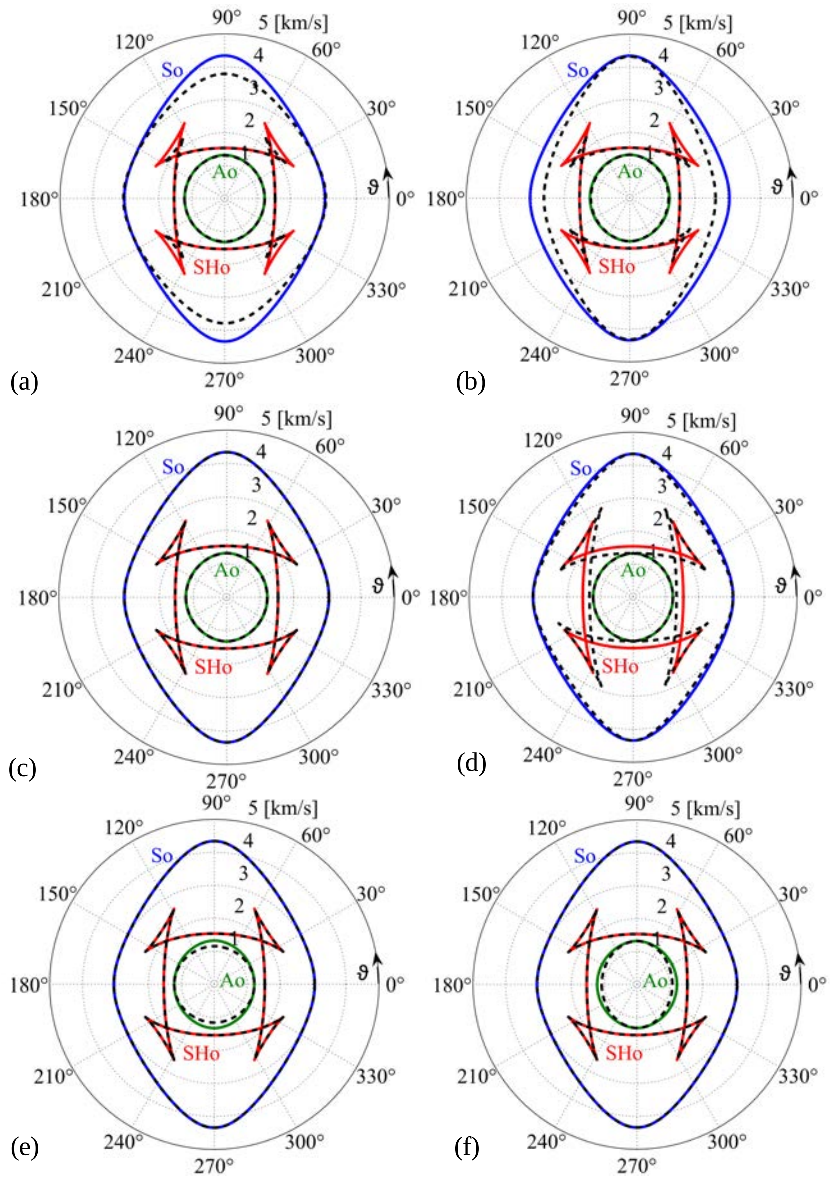

Figure 3. Influence of the Material Parameters on the Energy Velocity curves for a reduction of 25% in: (a) E_1, (b) E_2, (c) E_3, (d) G_{12}, (e) G_{13} and (f) G_{23}.

It can be seen that both variations of E_1 and E_2 have a strong influence on the velocities for the S_0 mode. These influences are reflected for the SH_0 mode only on its caustics and are practically not noticeable for the A_0 mode. The shear modulus G_{12} has a slight influence on the velocities of the S_0 mode at ±45° (and mirrored angles) direction and almost no influence on the 0°/90° direction. The A_0 mode is nearly not affected. However, the effect on changing G_{12} is quite strong for the SH_0 mode. The shear moduli G_{13} and G_{23} have a strong influence on the A_0 mode and almost no influence on the S_0 and SH_0 mode.

EXPERIMENTAL STUDIES

Experimental results are presented for two different plates. First, a CFRP plate made of 4 equal layers with a total thickness of 1.7*mm* and stacking of $[0\ 90\ 90\ 0]_s$ is studied. Nominal material parameters of the UD layers are E_1=122*GPa*, E_2=10*GPa*, G_{12}=G_{13}= 7.4*GPa* and G_{23}=5.4*GPa*. Temperature tests were conducted in a temperature-controlled oven. During the test runs the temperature was raised stepwise up to T=60 ± 2°C. The temperature was measured by two PT100 sensor mounted on the plate opposite corners. The effects of surface wetting on ultrasonic wave propagation are also studied. Results are depicted below in Figure 4.

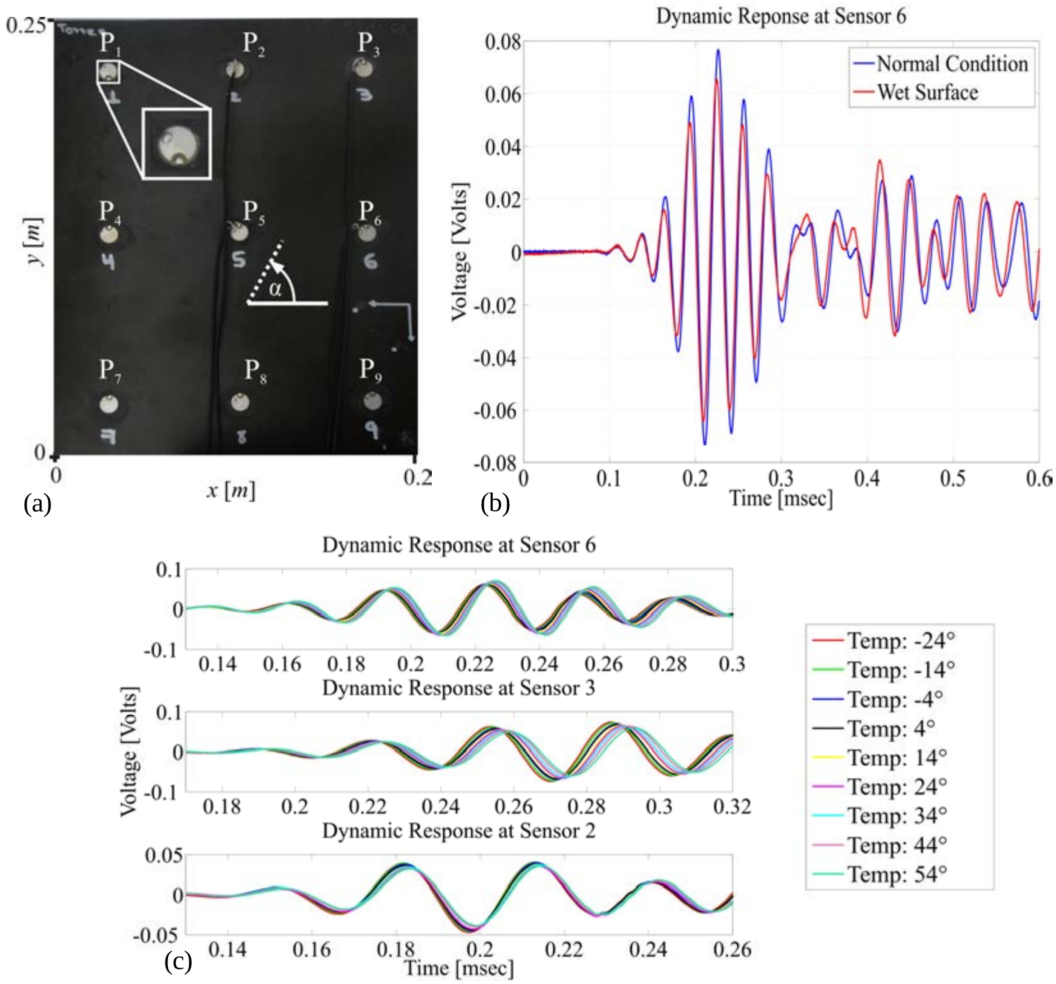

Figure 4. EOC Influences: (a) Experimental Setup, (b)Wet Surface Effect, (c)Temperature Effects on Wave Directionality.

Figure 4(a) shows the structure with dimensions 200*mm*×250*mm*. Nine piezoelectric transducers PIC151 from PI Ceramics were attached to the surface of the structure. The structure was excited by a piezoelectric transducer located in the middle of the structure. The excitation voltage signal is a 12*Volts* Hann-windowed toneburst with a carrier frequency of 30*kHz* with 5 cycles. Figure 4(b) shows that the shape of the signal changes significantly due to the wet surface influence. The influence of the variation in temperature also causes a change of structural dynamics. The dynamic response signal of sensor number two and three decreased monotonically in peak-to-peak magnitude with increasing temperature (Figure 4(c)). Interestingly, the inverse effect was seen in sensor number one. According to experimental results depicted in Figure 4(c), the increase in the temperature causes a right time-shift of the dynamic responses. Inversely, the decrease in the temperature causes a left shift. The reason of these time-shifts is both thermal expansion and changes in wave velocities with temperature. The attenuation of Lamb wave can be regarded to both wave dispersion as a result of frequency dependent phase velocities and attenuation loss due to frequency/temperature dependent material damping. An analysis of the separate contributions of both effects is not presented here. A second plate made of six equal layers with a total thickness of 3*mm* made of roving glass composite laminate from Bond Laminates GmbH was studied. The experimental setup and results are depicted in Figure 5.

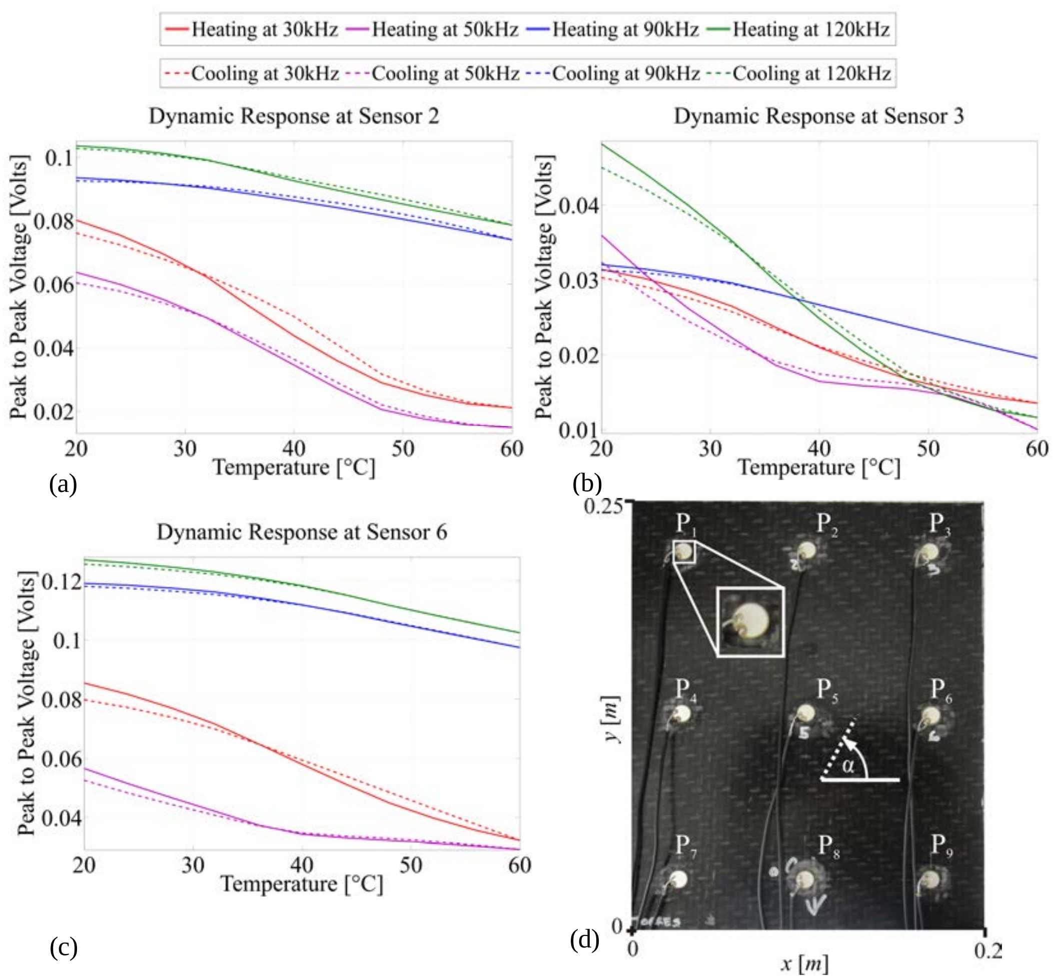

Figure 5. Temperature Gradient Effect on Peak-to-Peak Amplitudes of A_0 Mode: (a) Sensor 2, (b) Sensor 3, (c) Sensor 6 and (d) Experimental Setup.

Figure 5(d) shows the structure with dimensions 200*mm*×250*mm*. In a similar manner to the first CFRP plate, nine piezoelectric transducers were attached to the surface of the structure. The A_0 mode was selected in this study for the analysis of the influence of temperature gradient sign in the mode amplitude changes. Mode identification was accomplished based on dispersion features and energy distribution analysis as proposed by Torres and Fritzen [13]. The excitation signal was the same as in the previous example. The first effect that can be noted from Figure 5(a-c) is the change of amplitudes for a given frequency and orientation of the sensor. This effect is explained due to the changing ratio of displacement and stress amplitudes with respect to the frequency and angular orientation for a particular mode along the plate thickness. The knowledge of these wave propagation phenomena plays a critical role in the selection of the optimal inspection frequencies for the improvement of the sensitivity and for optimization of sensor networks in terms of sensor placement and number of sensors. It can be observed as well that the temperature gradient has a strong effect on the trajectories of the peak-to-peak amplitudes with respect to the heating or cooling cycles. It is good to bear in mind that the capacitance of piezoelectric (PZT) materials is known to be temperature sensitive. As temperature increases, the capacitance value of the PZT normally increases and this effect modifies the response of the sensor. Even when not depicted for this plate, the dynamic response signals of all sensors decreased monotonically in peak-to-peak magnitude with increasing temperature

CONCLUSIONS

The goal of this study was to illustrate the effects of environmental and operational condition sources of variability on wave propagation velocities, directionality and attenuation for composite materials, and bring their significance into focus for the proper development of structural health monitoring systems and damage detection algorithms. Influences such as temperature and changing operational conditions, which modify the structural dynamic responses, can be sufficient to disguise any changes correlated to damage to a level that it might not be detected. These changes can be considered as one of the main disadvantages for implementing guided waves based techniques in real world applications. Numerical and experimental results have shown how environmental and operational conditions can adversely affect the performance of ultrasonic structural health monitoring systems due to the fact that ultrasonic waves are sensitive to these changes as well as to damage. This is of special attention in baseline-based methods where the detection and characterization of damage is performed normally by means of metric indices by comparison of two dynamic response signatures. The effect of temperature on the transducer performance was not studied here. Nevertheless, it has been shown that these effects are significantly less than the effect of temperature on wave propagation within the structure. The authors are currently investigating the development of an improved modeling technique incorporating the effects of variable temperature in wave propagation and sensor response as well as the analysis of sensor fault detection. The development of improved and accurate modelling, and efficient simulation tools will help for the development of virtual SHM system design.

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REFERENCES

1. Fritzen, C.-P., G. Mengelkamp, and A. Guemes. *Elimination of temperature effects on damage detection within a smart structure concept*. In *Proceedings of the 4th IWSHM*, Stanford, CA: DEStech Publications, Inc., 2003, pp. 1530-1538.
2. Moll, J., P. Kraemer, and C.-P. Fritzen. *Compensation of Environmental Influences for Damage Detection using Classification Techniques*. In *Proc. 4th EWSHM*, Krakow, Poland: DEStech, 2008.
3. Raghavan, A. and C.E.S. Cesnik, *Effects of Elevated Temperature on Guided-wave Structural Health Monitoring.* Journal of Intelligent Material Systems and Structures, 2008. 19: pp. 1383-1398.
4. Lu, Y. and J.E. Michaels, *Discriminating damage from surface wetting via feature analysis for ultrasonic structural health monitoring systems.* Review of Progress in QNDE, 2008. 27(1): pp. 1420-1427.
5. Croxford, A.J., J. Moll, P.D. Wilcox, and J.E. Michaels, *Efficient temperature compensation strategies for guided wave structural health monitoring.* Ultrasonics, 2010. 50(4-5): pp. 517-528.
6. Kraemer, P., I. Buethe, and C.-P. Fritzen. *Damage detection under changing operational and environmental conditions using Self Organizing Maps*. In *Proceedings of SMART 11*, Saarbruecken, Germany, 2011.
7. Sohn, H., *Effects of environmental and operational variability on structural health monitoring.* Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2007. 365(1851): pp. 539-560.
8. Scalea, F.L.d. and S. Salamone, *Temperature effects in ultrasonic Lamb wave structural health monitoring systems.* Journal of the Acoustical Society of America, 2008. 124(1): pp. 161-174.
9. Torres Arredondo, M.-A. and C.-P. Fritzen, *A Viscoelastic plate theory for the fast modelling of Lamb wave solutions in NDT/SHM applications.* Ultragarsas (Ultrasound), 2011. 66(2): pp. 7-13.
10. Mindlin, R.D., *Influence of rotary inertia and shear on flexural motion of isotropic elastic plates.* J Appl Mech-T ASME, 1951. 18: pp. 31-38.
11. Torres Arredondo, M.-A., M.M. Ramirez Lozano, and C.-P. Fritzen, *DispWare Toolbox - A scientific computer program for the calculation of dispersion relations for modal-based Acoustic Emission and Ultrasonic Testing*. 2011: University of Siegen, Siegen, Germany.
12. Torres Arredondo, M.-A., H. Jung, and C.-P. Fritzen. *Towards the development of predictive models for the system design and modal analysis of acoustic emission based technologies*. In *Proceedings of the 2nd IWSDS*, Krakow, Poland, 2011.
13. Torres Arredondo, M.-A. and C.-P. Fritzen, *Characterization and classification of modes in acoustic emission based on dispersion features and energy distribution analysis.* To be published in "Journal of Shock and Vibration", 2011.