Analytical and Experimental Investigation of Environmental Influences on Lamb Wave Propagation and Damping Measured with a Piezo-Based System

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ABSTRACT

One of the main concerns in structural health monitoring (SHM) for composite materials is to discern between changes that are related to actual damage in the structure and changes that originate from non-damaging alterations of the material or the survey system. For both the layout of a piezo-based system (i.e. mainly the sensor/actuator area density) and the interpretation of the acquired data, the changes of the viscoelastic material properties due to normal environmental factors as temperature or moisture absorption have to be considered. Additionally, the SHM system itself and the coupling adhesive used to connect it to the material can be influenced by this factors. Without a strategy to account for those influences, a high false alarm rate has to be expected.

In this presentation, experimental and analytical investigations of a SHM system based on Lamb waves measured with surface applied piezoelectric sensors are presented. The influence of temperature and humidity on the measured velocity and damping coefficients is shown as well as the high influence of both factors on the excitability of Lamb waves. Potential and limitations of analytical methods to describe the measurement system and the temperature/humidity-dependence of the piezoelectric elements properties, the adhesive layer and the material itself are investigated.

INTRODUCTION

Lamb waves, which are ultrasonic waves propagating between two parallel surfaces, have gained large amounts of attention from the SHM community during recent years [1,2]. Due to their 2-dimensional propagation within plates, they have the potential of being used as a monitoring tool to evaluate size and position of local damages, e.g. due to impact events, or global changes within the material, for example due to humidity absorption [3], fatigue-related property degradation [4] or thermal damage [5], in large, plate-like structures.

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One of the main obstacles on the road to a large scale use of Lamb wave based SHM is the difficulty to discern between signal changes resulting from actual damage, and changes due to non-damaging influences. The two most basic tasks of a SHM are the detection and the localisation of damage [6]. Common active methods decide whether a damage occurred based on the comparison of the signal obtained while the structure was in a pristine state and the signal measured after the structure was in use for a certain amount of time. Methods to compare the signals can include the evaluation of the changes in amplitude and velocity of the measured wave modes or various other features derived from them (e. g. RMS, kurtosis, features of the signal in the frequency domain and many more). For SHM systems, which integrate a sensing technology into the monitored structure, these values do not solely change due to actual damage being introduced to the material. Instead, the sensors response is highly sensitive to a number of factors influencing either the material and its properties or the sensing (and in case of an active system actuating) mechanism itself and its connection to the structure.

Fig. 1 shows a schematic view of a typical active pitch-catch-system , consisting of two piezoelectric elements bonded to the material surface and the auxiliary equipment. The main goal of SHM in the configuration shown is to obtain a reliable information about the existence of damage between the actuator and the sensor.

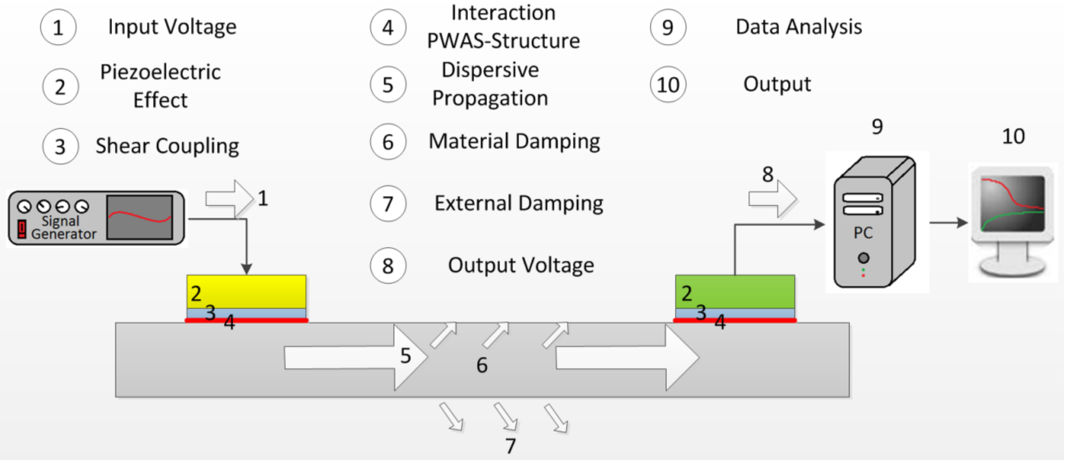

Figure 1. Principle of a Lamb Wave measurement using an active surface applied piezoelectric system in a pitch-catch configuration.

The challenge in creating a reliable SHM system is the fact that the sensor response as a whole depends not only on the structures and the SHM systems health (health being the absence of damage), but also on the state both the structure and the parts of the SHM system are in. To work reliable, the system has to be robust during the whole live cycle of the structure monitored. This is a central challenge of an integrated SHM system: while Lamb waves are highly sensitive for various damages, they (and most common SHM systems themselves) are also sensitive to a number of non damage induced changes of the material or its surroundings.

The reason is obvious from fig. 1: every part of the transmission process between the voltage application and the response measurement that is sensitive to changes unrelated to damage will change the sensor response, if such changes occur. Such factors include the aforementioned humidity absorption (changes material properties and properties of the adhesive layer), temperature changes (influences piezoelectric and viscoelastic properties of both the material and the piezoelectric elements), mechanical loads, relaxation processes and matrix ageing. If either the localization or the evaluation of the damage are influenced by these factors, the risk of false positives and/or false negatives will rise.

This paper describes the impact of such influences and their relevance for both the layout of Lamb wave based SHM systems and the localization and evaluation of damage, measurements were performed on materials exposed to varying environmental conditions. Additionally, an analytical method to account for such changes is discussed and its applicability for real structures is discussed, using a CFRP spar as an example.

EXPERIMENTAL INVESTIGATION

In order to obtain general information about the nature and magnitude of the environmental impact on lamb wave measurements, a set of experiments was performed under varying environmental conditions. The set-up and the results are described in the following paragraphs.

Experimental Set-Up

The experiments were performed with a set-up as shown in fig. 2. The test plates made of RTM6 with an UD reinforcement of 12 layers of G1157 D1300 Injectex were equipped with 10 piezoelectric sensors (diameter 7 mm, thickness 0.2 mm, Material APC 850). The adhesive used was M-Bond 200. The plates were roughly 500x500mm² in size and a layer of sealing mass was applied to the edges to prevent reflections. The sensor responses to an excitation by a Hann-windowed sinusoidal burst of three counts length were measured in the frequency range of 15 to 450 kHz. The specimen were subjected to varying temperatures in a Memmert ULE 700 oven and to varying environmental conditions (70°C and 85% humidity) in a Vötsch VC0018 environmental chamber. The Lamb wave measurements were repeated outside of the environmental chamber in regular intervals after allowing the plate to cool down. The signal generator used was a HP 33120A, while the oscilloscope was a TDS 3014B. The input signal was amplified using a Krohn-Hite 7602 wideband amplifier. 512 measurements were taken and averaged at each frequency.

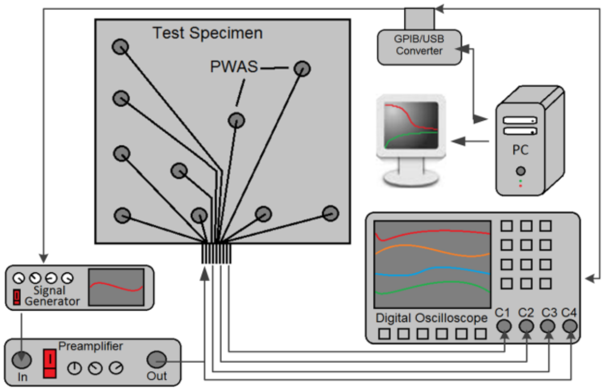

Figure 2. Experimental Set-Up.

Influence of Temperature Changes

For in-use vehicles and structures exposed to varying climates , temperature changes are generally unavoidable. Due to the temperature dependence of mechanical properties, combined with the anisotropic nature of many carbon fibre reinforced plastics and the different thermal expansion coefficients of the materials of the composites, these changes result in different wave velocities and damping coefficients in the structure, depending on the propagation direction. Additionally, the piezoelectric and mechanical properties of the sensors/actuator and the properties of the adhesive used to bond them to the structure are a function of the temperature. The impact of changing temperatures on both the response amplitude and the measured dispersion curves of wave velocity and damping is shown in fig. 3 and fig.4.

Fig. 3 shows measured response amplitude of sensors ~150 mm away from the actuator. The results are normalized to the peak voltage of the actuating signal.

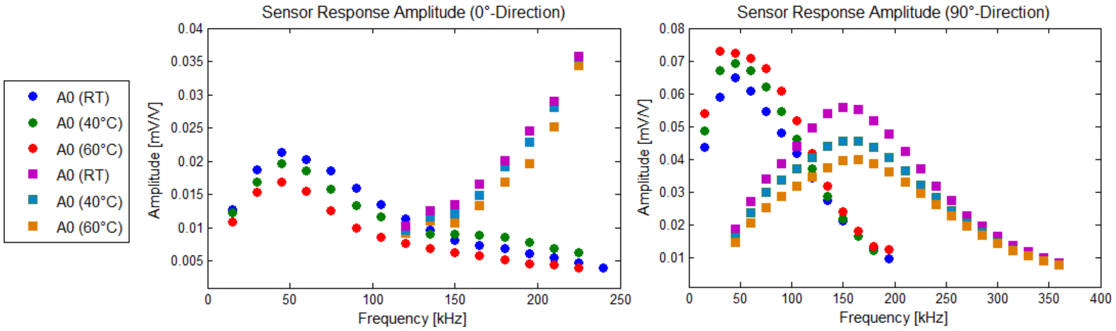

Figure 3. Response amplitude of the lowest wave modes after propagating 150 mm from the actuator.

Both the impact and the anisotropic nature of the influence of the temperature on the response amplitude of the sensor are visible. While the response amplitude drops with rising temperature in the direction of the fibres, it rises perpendicular to them. The reason for this behaviour is the interference of the various changes: while some are independent of the direction of the waves, e.g. the piezoelectric properties and the stiffness of the bonding layer, others are a function of the propagation angle, e.g. material damping or the ratio between the stiffness of the actuator and the material of the structure.

In contrast, all velocities measured drop. This is due to the fact that the velocity is gained from the signal of two sensors, which reduces the influence to the changes of the material of the waveguide itself. The materials elastic properties drop, which leads to a lower velocity. Its viscous properties, however, show an inconsistent behaviour with the A_0-modes damping coefficient dropping and S_0- and SH_0-mode rising.

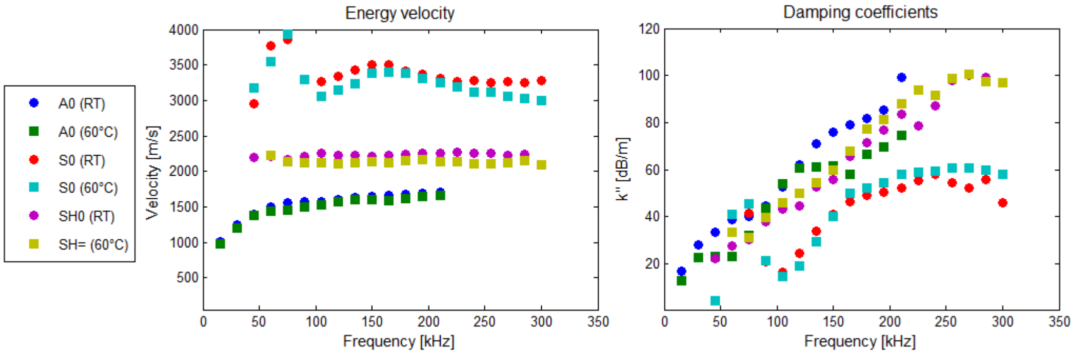

Figure 4. Changes of velocity and damping of waves propagating along an angle of 45° to the fibres.

The drop of A_0-damping is also observed perpendicular to the fibres. Sensitivity analysis performed in [3] and [10] show that the viscous parts of the out of plane shear properties influence A_0 damping coefficients in these directions while not significantly influencing the other modes. Reasons for such a loss in the imaginary parts could be partial redrying during the measurements or thermally induced stresses.

Influence of Humidity Absorption

Compared to temperature changes, humidity absorption modifies fewer properties of the system depicted in fig.1 because the mechanical and piezoelectric properties of the piezoceramic material of the sensors/actuators are not influenced. The impact of this changes, however, is still remarkable large, especially for the amplitudes measured. Fig. 5 shows the development of the sensor response amplitude of the lowest Lamb wave modes propagating perpendicular to the fibre over time and frequency. The loss of amplitude is consistently high for all wave modes and propagation directions which were observed.

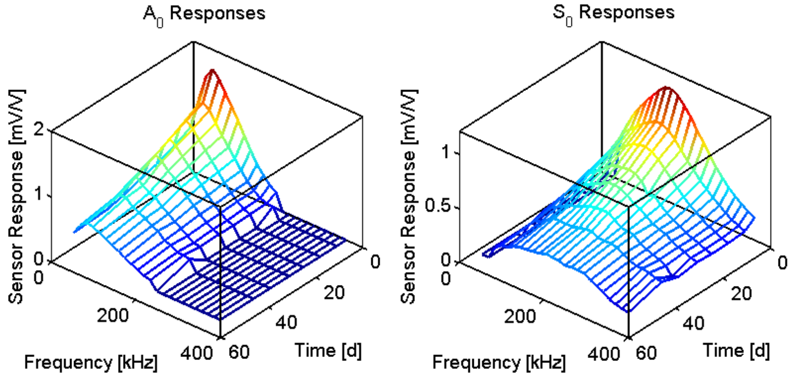

Figure 5. Development of A_0 and S_0 amplitude during conditioning at 70°C and 85% Humidity.

From the figure, the importance of a method to account for humidity-related amplitude changes becomes apparent. These results show that methods relying on changes of the signal amplitude or values derived from it have to account for changes due to humidity, and that during the design of a SHM system the sensor density has to be chosen large enough account for the lower response after conditioning. In comparison to the large changes of the amplitude, the changes in both velocity and damping coefficient are found to be relatively small.

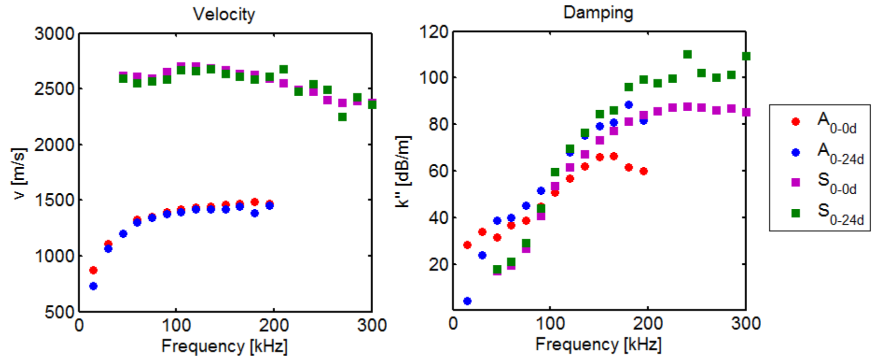

Figure 6. Changes of the wave velocity and damping coefficients perpendicular to the fibres after 24 days of conditioning.

Calculating the theoretical amplitude ratio between an excited wave directly at the actuator (assumed to be constant, which would be the case if the only variables were the viscous material properties) and at the first sensor, one can show that the measured damping coefficient changes account for only around 25% of the lower sensor response. The remaining drop therefore has to be a result of the actuation and sensing process itself and underlines the importance of the actual SHM system for the robustness and reliability of the measurements performed.

ANALYTICAL INVESTIGATION

Common approaches to identify and localize damage using Lamb waves often rely on the comparison of one or a set of features of the sensor response with a baseline measured in a known pristine state and evaluating if these features are inconsistent. To account for a dependency of this features on influences unrelated to the damage, the baseline or the features used for the definition of a healthy state have to be a function of these influences [7, 8]. While it is possible to generate baseline data for some structures and environmental values with a reasonable amount of effort (for instance temperature), other, slowly developing influences like humidity absorption or stress relaxation are much more difficult to incorporate in such an approach.

As a solution for this problem, predict the changes of the Lamb wave features used for damage identification can be predicted on an analytical base, using material properties gathered from coupon specimen. Depending on the features, such an approach has to take into account any of the components of the SHM system used that influence said feature and are in turn changed by the non-damaging factor under investigation. For the signal amplitude, this requires knowledge of the mechanical properties and geometry of the structure, the adhesive and the sensor/actuator as well as the piezoelectric properties of the last two [9]. For relative measurements, such as changes in the velocity and the damping coefficient, the information needed is reduced to the viscoelastic properties of the material itself, if the assumptions are made that all changes influence the sensors equally and that the sensors are far from the actuator.

Based on this assumptions, the changes of the velocity and the damping coefficient after humidity saturation were predicted using 3rd order plate theory and a hysteretic damping model similar to [10]. The viscoelastic material properties were obtained using DMA (dynamic-mechanical analysis) measurements of dry and saturated samples and a reduced parameter material model as outlined in [11]. The results of this approach for the two lowest Lamb wave modes are given in Table 1.

Table 1. Measured and analytically predicted changes of velocity and damping.

Mode	In Fibre Direction				Perpendicular to the Fibres			
	Velocity		k''		Velocity		k''	
	Exp. [%]	Pred. [%]	Exp. [%]	Pred. [%]	Exp. [%]	Pred. [%]	Exp. [%]	Pred. [%]
A_0	-2.2	-1.6	+16.9	+18.9	-1.1	-1.2	+16.4	+7.1
S_0	-1.8	-1.3	-6.0	-6.2	-1.4	-1.7	+11.3	+7.6

Experimental and predicted values show a good qualitative agreement, whereas the quantitative difference, esp. for the damping coefficients perpendicular to the fibres, is quite large. Predictions such as these or similar ones for other environmental factors could be used to alter the borders of the acceptable difference between baselines and measurements after exposure to a changing environment. Additionally, the knowledge of the changes in damping behaviour are important for the dimensioning of both active and passive SHM systems, as they influence the area covered by an actuator.

LIMITATIONS OF ANALYTICAL APPROACHES

One central problem with any baseline approach where the baseline is a function of multiple factors is the need for a method to select the correct sub-baseline. An example for this is the analytical approach described before: while it is possible to scale the expected velocity and damping using this method and data gathered from DMA measurements, exact information about the humidity content of the material is needed. Additionally, the actual humidity inside a real structure will almost always depend on the place in the structure (example: areas with bilge water) and, most importantly, the time it is exposed to a certain environmental condition. As the environment changes, the humidity over the thickness will vary, making exact analytical predictions virtually unattainable.

Another hindrance is the SHM system itself. To be able to use the full extent of the information in a baseline and the sensor response, one has to account for the impact of the influences on the system itself. This influences, however, vary with the specific parameters which describe the system, such as the property of the piezoelectric elements and the adhesive. As tolerances exist for all these factors, an analytical model can't achieve results as good as that of a baseline approach were the baseline is gathered from the same structure for whose evaluation it is later used.

A third problem to keep in mind is the complex sensor response in real structures, which often include echoes, interferences and mode conversions. To exemplarily show this on a real structure, an LCF spar used as a technology demonstrator for various sensor concepts [12] was equipped with MFC sensors for Lamb wave excitation and measurement. The spar, which is shown in fig. 7, was exposed to a moist climate at room temperature for 5 weeks. Fig. 8 shows both the complex signal with no immediately distinguishable Lamb wave modes at 45 kHz and the changes due to the environmental conditions.

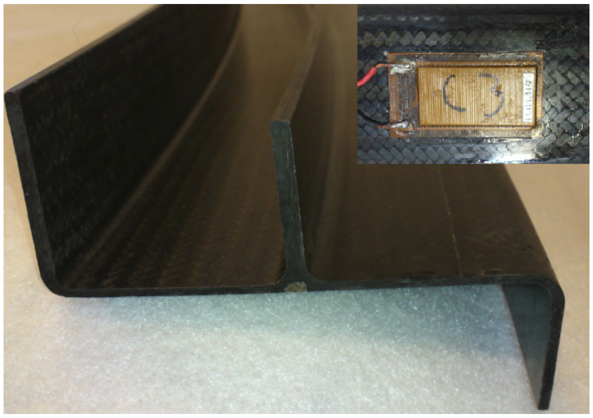

Figure 7. LCF spar (large picture) and MFC Sensors (small picture).

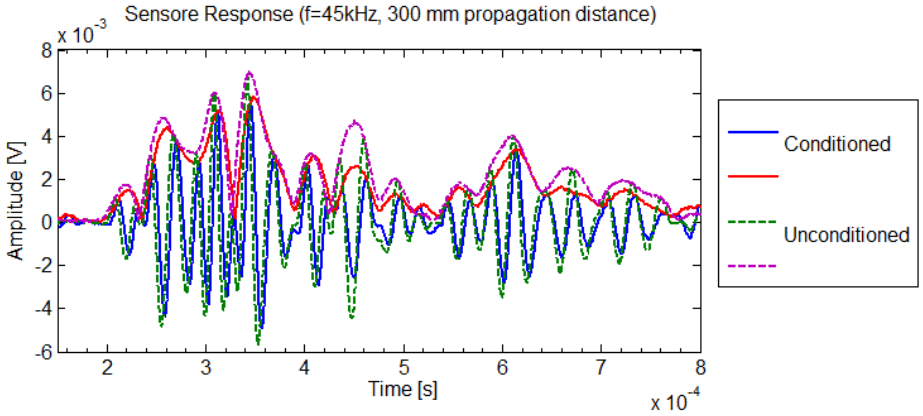

Figure 8. Sensor response of an MCF sensor applied to an LCF spar in 300 mm distance from the actuator, excited by a 3-cycle windowed sinus signal at 45 kHz, before and after conditioning.

While there is a visible drop of the excited amplitude that is consistent over most of the recorded signal, one can see that an approach to account for this changes in amplitude based on simple correction factors would not work due to the large differences in the ratio between the conditioned and the unconditioned signal. These are most likely a result of small velocity shifts, which lead to changing interference between parts of the Lamb wave modes reflected from the spars sides.

CONCLUSIONS

The large impact of environmental factors such as temperature and humidity absorption on both the excitation and propagation of Lamb waves shown in this work is a fact that has to be considered during both the design and the usage of a Lamb-wave based SHM system. It was shown that esp. humidity absorption can lead to a drastically decreased sensor response, thereby increasing the sensor density needed to cover a specific area. Additionally, algorithms to identify damage based in any way on the signal amplitude have to account for this non-damage related changes to prevent false alarms and false negatives.

While it is possible to account for some changes via extensive baseline catalogues and/or methods to predict the changes of some signal features due to these factors, the application of such methods in real structures seems improbable due to a) the nature of some of these factors (e.g.: humidity, which will generally vary both over the thickness of the waveguide and with the locally varying environmental exposure) and b) the complex geometry of real structures, whose stiffness changes and borders produce reflections, mode conversions and therefore interferences at the sensors.

Any SHM system for the permanent surveillance of fibre reinforced plastics will therefore have to prove reliability and robustness for all possible non-hazardous material states. For this, the main challenge is to design both the system and the damage identification algorithms in a way that the features used for damage identification remain distinguishable and detectable at all times.

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