Estimation of Composite Plate Attenuation

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***Abstract*—A new method based on Ping He's technique for simultaneous measurement of frequency dependant thickness and attenuation was developed without any need of a priori knowledge of the material parameters. The thickness and attenuation coefficient for longitudinal wave were measured in a thin specimen of glass fiber reinforced plastic produced by Resin Transfer Molding. A 5 MHz pulse of 0.1 μs duration was used as excitation signal. Mean error and standard deviation of the frequency dependant thickness are used to compare both techniques. The new method has demonstrated to be more accurate than conventional Ping He's technique, and can be implemented automatically thus saving processing time and increasing accuracy. Measurement of the attenuation coefficient is achieved using the frequency dependent thickness without requiring any additional parameter of the material.**

***Index Terms*—Composite characterization, ultrasound attenuation, ultrasonic measurement, thickness estimation.**

I. INTRODUCTION

The number of new composite materials has greatly increased in recent years, given to its low cost, ease of manufacture and the large number of applications they have. As these are experimental materials, it is essential to have the tools to control and evaluate the manufacturing process and the behaviour of their characteristics with time and use. Ultrasound attenuation and dispersion (changes in phase velocity with frequency) are two material properties directly related to the characteristics of the material and widely used in non-destructive evaluation and material characterization.

Although it can be found a lot of techniques in literature for frequency dependent attenuation measurement [1]–[5], Ping He's technique [6], [7] is one of the most used due to its ease and because it does not need any *a priori* knowledge of the material characteristics. Using simultaneous pulse-echo and through-transmission immersion measurements, it is able to provide the frequency dependent thickness and attenuation. It is not an exact method and has several limitations [6], [7], but in spite of them, it still provides very useful results when the parameters of the material are unknown, which is especially interesting when analysing fiber reinforced RTM composites, whose final inner composition is difficult to control due to its fabrication process [8]–[11].

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Unfortunately, Ping He's technique requires manually fitting of the time shift applied to each signal in order to avoid the phase uncertainty due to phase unwrapping, thus it is not suitable for automatic material characterization.

In this work we propose a modification of Ping He's technique based on the use of cross correlation functions instead of the signals itself, thus avoiding the need of manually selection of the applied time shift.

Section II briefly reviews Ping He's technique and the proposed modification, and Section III shows the experiment setup and the results of the analysis. Finally, Section IV summarized the most relevant conclusions of this work.

II. MATERIAL CHARACTERIZATION

A. Ping He's Method for Measurement of Frequency Dependent Thickness and Attenuation Coefficient

The proper characterization of the attenuation in the frequency domain requires accurate measurements of the thickness of the specimen to be analysed, which also implies a precise knowledge of the propagation speed in the material. Since our hypothesis is precisely the lack of any of these parameters, the first task is to obtain a measurement of the thickness with frequency, for which we use the scheme of immersion measurements such as the one shown in Fig. 1 according to the procedure described in [6].

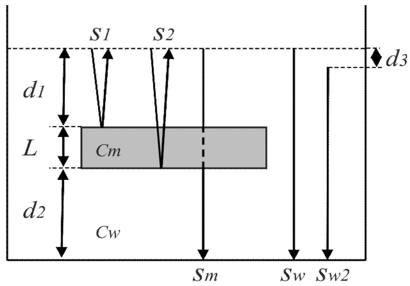

Fig. 1. Experiment set-up of through-transmission and pulse-echo measurements.

The advantage of this method is that it only requires three measurements while keeping the layout of the transducers. First, the specimen (thickness L and sound velocity c_m) is inserted between transducers at appropriate distances (d_1 and d_2). Then, transducer T_1 sends a pulse and simultaneous reflected and passed through signals are recorded in transducer T_1 and T_2 respectively as $s_p(t)$ and $s_s(t)$. Note that $s_p(t)$ contains reflections from front and back surfaces from the specimen, which will be later gated and separated as $s_1(t)$ and $s_2(t)$ respectively. Finally, the specimen is removed and transducer T_1 sends a pulse through the water path, which is received in transducer T_2 and recorded as $s_w(t)$. Although not strictly necessary, an additional water path measurement $s_{w2}(t)$ can be done changing the distance between transducers (d_3) for an accurate measurement of the velocity in water.

The attenuation coefficient of the specimen under analysis can be obtained according to Ping He's technique from the amplitude spectra of the transmitted and reflected pulses. Let's call $A_w(f)e^{-j\theta w(f)}$, $A_s(f)e^{-j\theta s(f)}$, $A_1(f)e^{-j\theta 1(f)}$ and $A_2(f)e^{-j\theta 2(f)}$ the Fourier transform of $s_w(t)$, $s_s(t)$, $s_1(t)$ and $s_2(t)$ respectively. Then, attenuation is obtained using [7]

$$\alpha(f)=\frac{20}{L(f)}\left[Log\left(\frac{A_1(f)}{A_2(f)}\right)-Log\left(\frac{A_w(f)}{A_s(f)}\right)\right], \quad (1)$$

with $L(f)$ as [7]

$$L(f)=\frac{c_w}{4\pi f}\left[\left(\theta'_2(f)-\theta_1(f)\right)+2\times\left(\theta_w(f)-\theta_s(f)\right)\right], \quad (2)$$

where $\theta_w(f)$, $\theta_s(f)$, $\theta_1(f)$ and $\theta'_2(f)$ are the phase spectra of $s_w(t)$, $s_s(t)$, $s_1(t)$ and $-s_2(t)$ respectively (the negative sign of $s_2(t)$ is necessary to take into account the inherent 180º inversion of the second echo due to reflection in back surface), and c_w is the speed of sound in water. Note that (2) does not depend of the speed of sound in the specimen, so its calculation is not required.

To avoid the phase wrapping, Ping He [6], [7], [9] suggested to circularly shift gated signal $s_i(t)$ to its centroid. Then, phase spectrums are as follows

$$\theta_i(f)=\varphi_i(f)+2\pi f t'_i, \quad (3)$$

where $\theta_i(f)$ is the absolute phase spectra of $s_i(t)$, $\varphi_i(f)$ is the phase spectra of the shifted version of $s_i(t)$, and t'_i is the time shift applied, which should include the difference between windows origin (trigger delay) if any. Additional shifting can be applied to reduce any possible discontinuity in the selected frequency range, and should also be included in t'_i.

Now, using (3) in (2), thickness $L(f)$ can be calculated as

$$L(f)=\frac{c_w}{4\pi f}\left[\left(\varphi'_2(f)-\varphi_1(f)\right)+\right.$$
$$\left.+2\times\left(\varphi_w(f)-\varphi_s(f)\right)+2\pi f\left(t'_2-t'_1+2t'_w-2t'_s\right)\right]. \quad (4)$$

B. Modified Ping He's Technique

The above method used to calculate the phase has some problems: First, selecting the centroid of the signal as reference point for time shifting does not lead to a symmetrical wave of pseudo-linear phase, which is especially true if the applied pulse is not symmetrical and has been severely attenuated and/or dispersed. Second, according to the original method, time shift has to be applied in samples, thus the real centroid of the signal will not necessary coincides with a sampled time position. Even if time shifting is performed in a subsample basis, additional arbitrary time delay have to be added to all signals to achieve the desired pseudo-linear phase, which have to be done manually. Thus, limitations of the procedure can be summarized as: it cannot be done automatically, it has to be applied to 4 signals and it has a deviation from the true values due to the arbitrary time shifting and gating.

To overcome these problems, we suggest to work with the cross correlation between the signals. Correlation in frequency domains implies multiplication by the conjugate version of one of the spectrums, thus the contribution of all the sources of dispersion (transducers, water-path and transmission/reflection coefficients) are negated, so in the resulting phase difference only information of the specimen remains. Furthermore, a maximum of the correlation is the best symmetry point leading to the best pseudo-linear phase fitting. Thus, if we calculate $r(t)$ as the inverse Fourier transform of $R(f)$ and circularly shift it to the left in a subsample basis until its maxima coincides with cero, we will have the best fit to the pseudo-linear phase difference.

For the through-transmission experiment, cross correlation between $s_w(t)$ and $s_s(t)$ is calculated as

$$X_{ws}(f)=A_w(f)e^{-j\theta_w(f)}\times\left(A_s(f)e^{-j\theta_s(f)}\right)^*=$$
$$=A_w(f)A_s^*(f)\cdot e^{-j(\theta_w(f)-\theta_s(f))}=$$
$$=A_{Xws}(f)e^{-j\theta_{Xws}(f)}, \quad (5)$$

where $A_X(f)$ is the amplitude spectra of $X_{ws}(f)$ and $\theta_{Xws}(f)$ is its phase spectrum, which is actually the desired phase difference between the signals.

A similar procedure can be followed to obtain the phase difference between $s_1(t)$ and $-s_2(t)$. First, cross correlation between original full pulse-echo signal $s_{pe}(t)$ and $s_w(t)$ is calculated, which will produce a more compact version of both pulses thus easing its separation

$$X_{pew}(f)=A_{pe}(f)e^{-j\theta_{pe}(f)}\times\left(A_w(f)e^{-j\theta_w(f)}\right)^*=$$
$$=A_{pe}(f)A_w^*(f)\times e^{-j\left(\theta_{pe}(f)-\theta_w(f)\right)}. \quad (6)$$

Now, cross correlations can be gated in time domain choosing and optimized window and then transformed again into frequency domain for each reflected pulse obtaining

$$X_{s1w}(f)=A_{s1}(f)A_w^*(f)\times e^{-j\left(\theta_{s1}(f)-\theta_w(f)\right)}, \quad (7)$$

and

$$X_{s2w}(f)=A_{s2}(f)A_w^*(f)\times e^{-j\left(\theta'_{s2}(f)-\theta_w(f)\right)}. \quad (8)$$

Then, correlation between X_{s1w} and X_{s2w} is calculated and divided by $R_{ww}(f)$, the auto correlation of $s_w(t)$

$$X_{s2s1}(f)=X_{s2w}(f)\times X_{s1w}^*(f)/R_{ww}(f)=$$
$$=\left(A_{s2}(f)A_w^*(f)\times e^{-j\left(\theta'_{s2}(f)-\theta_w(f)\right)}\times\right.$$

$$\times A_w(f) A_{s1}^{*}(f) e^{-j(\theta_w(f)-\theta_{s1}(f))}\Big) / \left|A_w(f)\right|^2 =$$
$$= A_{s2}(f) A_{s1}^{*}(f) \times e^{-j(\theta'_{s2}(f)-\theta_{s1}(f))} =$$
$$= A_{s2s1}(f) \times e^{-j(\theta_{s2s1}(f))}, \quad (9)$$

where $A_{s2s1}(f)$ is the amplitude spectra of $X_{s2s1}(f)$ and $\theta_{Xs2s1}(f)$ its phase spectra, which is precisely the desired phase difference between the signals.

Now, $x_{ws}(t)$ and $x_{s2s1}(t)$ are calculated as the inverse Fourier transform of $X_{ws}(f)$ and $X_{s2s1}(f)$ respectively and circularly shifted in a subsample basis to the left until is maxima coincides with the origin.

Finally, the Fourier transform of the shifted versions of $x_{ws}(t)$ and $x_{s2s1}(t)$ are again calculated to obtain their respective phase difference $\varphi_{ws}(f)$ and $\varphi_{s2s1}(f)$ to be used in (4) as

$$L(f) = \frac{c_w}{4\pi f}\left[\varphi_{s2s1}(f) + 2\times\varphi_{ws}(f) + 2\pi f\left(t_{s2s1} + 2t_{ws}\right)\right], \quad (10)$$

with t_{sw} and t_{s2s1} the corresponding time shifts, which match exactly the time of flight between the signals, thus the steps followed to derive $L(f)$ will also provide the time of flights needed to calculate the speed of sound of the specimen. Note than in all the previous formulation a 180º shift has been applied to $s_2(t)$ to take into account the inherent inversion of the second echo due to reflection in back surface.

III. Experiment and Results

A. Experiment Setup

A typical setup for immersion experiment was used to develop the measurements according to Ping He's method (Fig. 1). Transmitter T1 was a 5 MHz wideband focused transducer IRY405 from NDT transducers LLC and receiver T2 was a composite 5 MHz transducer TF5C6 from Doppler Electronic Technologies. Such pair of transducers gives a frequency range of 0.5 MHz–7 MHz at -20 dB. The distance between transducer T1 and the specimen was set to the focal distance, i.e., 36 mm from front surface for T1 and T2 was placed at 10 mm from back surface.

The pulser-receiver used was SE-TX06-00, with sampling frequency of the acquisition system set to 100 MHz and sampling windows length adjusted in order to have all measurements of each experiment in the same time basis. A 100 ns 5 MHz pulse has been used as excitation.

A specimen of fiber glass reinforced plastic was analysed. Sample was produced by resin transfer molding, using non-woven chopped fiber mat and high flowability resin. One surface of the specimen was smooth (mold side) and opposite surface was uneven (vacuum bag side). Thanks to careful technological process porosity of the sample was very small. Sample had a variable thickness 1.6 mm–2.2 mm. 40 A-scan were acquired at different locations in steps of 0.5 mm moving the specimens along X axis with an automated XY scanner. At each particular position 25 A-scan were acquired and averaged to improve the signal-to-noise ratio (SNR).

Sound velocity in water was calculated using two measures with different distances between T1 and T2 and obtained values before and after each experiment were averaged, providing an accurate measurement for each experiment independent of temperature.

B. Results

Figure 2 shows the different stages of the proposed method. Figure 2(a), Fig. 2(c) and Fig. 2(d) show respectively an example of a through-transmission A-scan, a water-path A-scan and the corresponding inverse Fourier transform of their cross correlation calculated using (5). Figure 2(b), Fig. 2(d) and Fig. 2(f) show the corresponding pulse-echo A-scan, its cross correlation with the water-path A-scan and the inverse Fourier transform of the cross correlation using (6) between the gated signals marked with dotted rectangles. Note that in Fig. 2(d), the signal corresponding to the second reflection has been negated and multiplied by a factor of 20 only for visualization purposes, as its magnitude is very small compared with the result obtained with the first reflection.

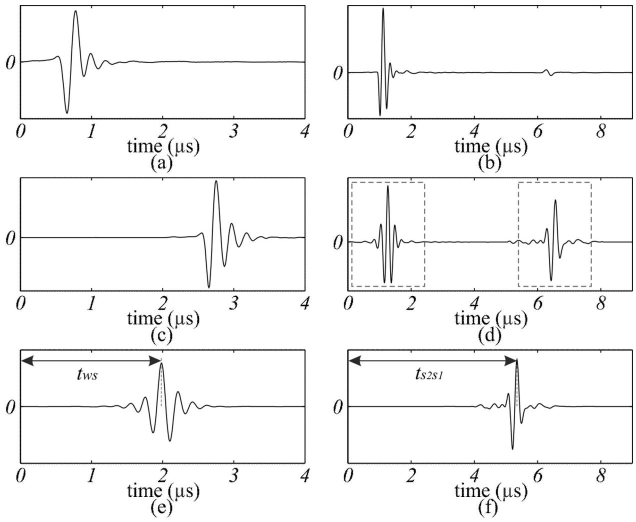

Fig. 2. Examples of A-scans and time shifting for epoxy specimen and 3 μs chirp. (a) Through-Transmission. (b) Pulse-Echo. (c) Water-Path. (d) Cross correlation of signals in (b) and (c). (e) Cross Correlation of signals in (a) and (c). (f) Cross correlation of gated signals in (d).

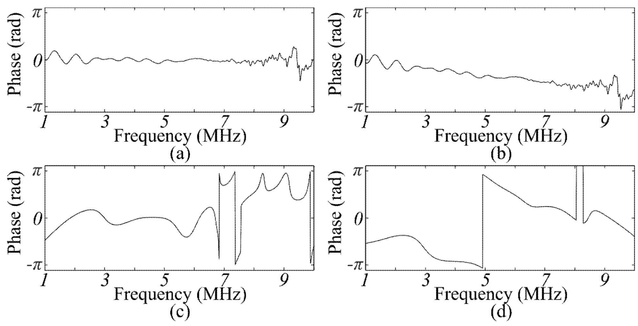

Fig. 3. Examples of phase spectra after time shifting. (a) and (c) using the new procedure for through-transmission and pulse-echo respectively, and (b) and (d) using Ping He's for through-transmission and pulse-echo respectively.

Figure 3 shows a comparison of the phase spectra obtained using the new procedure (left) and Ping He's (right). Time shift is completely removed using the new procedure (Fig. 3(a)) compared to Ping He's (Fig. 3(c)) results. Furthermore, even using manually shifting, Ping He's is not able to remove all phase jumps (Fig. 3(d)) in some scans, while results using the new procedure are free of jumps in all the band of interest (Fig. 3(c)) for all the scans.

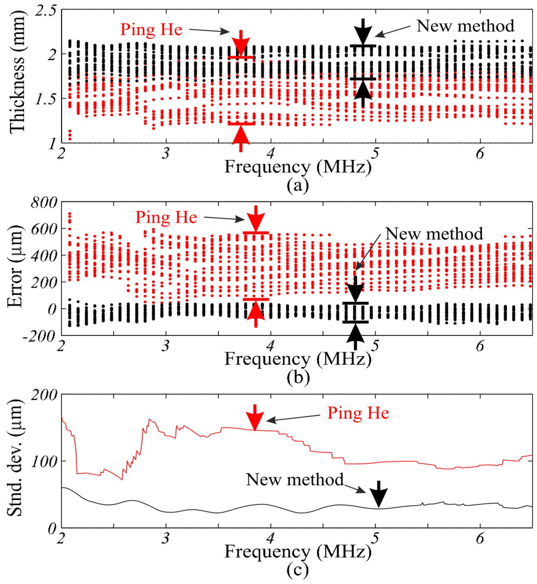

Fig. 4. Comparison of thickness obtained using Ping He's technique (red dots) and the new method (black dots). (a) Absolute thickness in mm (b) Bias in microns (c) Standard deviation in microns.

Figure 4 shows a comparison of the results obtained for the frequency dependent thickness using Ping He's technique (red) and the new method (black) for the considered fiber glass reinforced specimen. Figure 4(a) shows the thickness for all the scanned locations. As the thickness is not the same at each position, Fig. 4(b) shows the error in microns between the calculated thickness and the reference thickness (obtained by caliper measurement), and Fig. 4(c) presents the resulting standard deviation in microns.

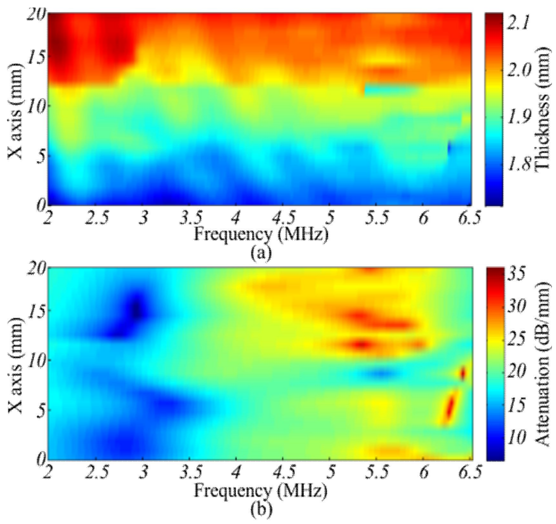

Fig. 5. Pseudocolor image of the (a) frequency dependant thickness in mm and (b) attenuation in dB/mm.

These figures clearly show the advantages of the new method, as both the error and standard deviation are lower than using Ping He's technique.

Finally, Fig. 5 shows the pseudocolor images of the thickness (Fig. 5(a)) and attenuation (Fig. 5(b)) for all the analysed area using (1) with the thickness obtained with the new method.

IV. CONCLUSIONS

In this work we have presented a new method for calculating the frequency dependent thickness and attenuation for composite materials based on Ping He's technique and cross correlations. Using cross correlations only two phase differences have to be calculated, instead of the four phases that needs the original technique, thus reducing the sources of error.

On the other hand, as phase contribution due to transducers, water-path and transmission/reflection coefficients are negated, only dispersion due to the specimen remains in the resulting phase differences. Furthermore, cross correlation maxima provide a better symmetry point than original centroid to achieve the desired pseudo-linear phase automatically, in addition that pulse compression achieved with correlation eases the gating of the reflected pulses, thus increasing the axial resolution and/or allowing the use of longer pulses.

Finally, if shifting is performed on a subsample base, the resulting time shifts provide directly the time of flight between signals that can be used to calculate also the velocity.

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