In Situ Damping Characterization for Improved Imaging in Structural Health Monitoring

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ABSTRACT

The damping of a material affects the distance over which guided waves can travel, determining the effective area of a structure which can be monitored by a given configuration of actuators and sensors in structural health monitoring (SHM). The attenuation of waves practically limits the efficiency of damage imaging approaches based on Time of Flight. More recent damage strategies exploiting propagation models such as Excitelet rely on the knowledge of material properties and damping has not been considered up to now. This paper presents the preliminary results of a method based on guided wave propagation for in-situ estimation of material damping. This parameter, together with other parameters such as Young’s modulus, Poisson’s ratio and density, could then be used in the propagation models used for damage imaging. The method evaluates the attenuation of a material by correlating time domain measurements, with model-based predicted dispersed versions of an excitation signal, generated by a piezoceramic actuator. Predicted dispersed versions of the excitation signal are generated by a propagation models using complex wavenumbers, where the imaginary parts represent the damping coefficient. The approach is first validated numerically using a finite element model (FEM) of three isotropic structures having different damping coefficients. In these models, the generation of a windowed burst onto the structure is simulated using an actuating bonded PZT. The time signal of the generated burst at the emitter is dispersed using propagation models. The damping is estimated using a genetic algorithm, by finding the optimal complex wavenumbers in the propagation model leading to the highest correlation between the FEM measurement measured and the model-based predicted dispersed time signals. An experimental assessment of the approach is then carried out on a 2.33 mm thick composite plate. Measurement points are taken using Lased Doppler Vibrometer (LDV). The results obtained in this work show the potential of the approach to estimate accurately the damping of a material.

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INTRODUCTION

The damping of a material affects the distance over which guided waves can travel. This parameter, combined with the attenuation, determines the effective area of a structure which can be monitored by a given configuration of actuators and sensors in structural health monitoring (SHM).

Time-of-Flight (ToF) approaches have been used within imaging techniques to process signals measured from the elements of sparse and compact arrays [2]. More recently, the Excitelet algorithm was proposed using dispersed versions of the excitation signal with a round robin procedure to image defects within the far field of the array [1]. This approach requires the knowledge of the phase velocity, which depends on the wavenumber, based on the mechanical and geometrical properties of the structure. The accuracy and reliability of this approach can be impaired by erroneous knowledge of the mechanical properties [6]. Traditional approaches can be used to determine a structure's mechanical properties [3, 4], but in order to increase the robustness of the Excitelet approach, recent methods based on guided wave dispersion were presented to indentify *in-situ* the mechanical properties of a structure [5].

Even if the damping of a structure is considered in the literature by calculating complex wavenumbers [8], at the moment, no imaging approaches considering the damping in their models have been found. Among the existing approaches used for damping estimation, modal analysis and Oberst beam are very popular approaches [7]. However, these require samples of the structure to estimate accurately the damping of a structure and the sensors cannot be embedded onto the structure.

In this paper, a technique based on guided wave propagation using bonded piezoceramics (PZT) as emitter and Laser Doppler Vibrometer (LDV) as receiver is used to assess the potential of guided waves for damping characterization. The long term objective of this work is to develop an in-situ methodology that could increase the robustness of imaging approaches. The approach proposed in this paper is based on the fact that guided waves are very sensitive to damping on long range propagation. Thus, this sensitivity is exploited to evaluate its potential to accurately characterize the damping of a material. The potential of this study is evaluated by both numerical and experimental assessment of the characterization algorithm. Section 2 presents the formulation of the approach, Section 3 presents the finite element model (FEM) assessment, and Section 4 presents the experimental assessment.

CHARACTERIZATION METHOD

Wave Propagation Model for a Circular Emitter

From the equation of motion for an elastic media, the displacement of dispersed guided wave at a certain distance *r* from the emitter can be calculated. In this paper, the dynamics of the actuator are neglected. Considering Cartesian coordinates on a plate of thickness 2*b*, the displacement component in the propagation direction for the first symmetrical mode S_0, u_1^s is given by [12]:

$$u_1^s(\omega) = \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\cos\beta b\cdot e^{-i\,(\xi_1 x_1+\xi_2 x_2-\omega t\,)}}{\beta\sin\beta b\, D_s(\xi)}\times$$
$$\left\{-\bar{F}_1(\xi_1,\xi_2)\left[\left((\xi^2-\beta^2)+\xi_1^2(\xi_2^2+\beta^2)\right)\cos\alpha b\sin\beta b+4\alpha\xi_2^2\sin\alpha b\cos\beta b\right]+\right.$$
$$\left.\bar{F}_2(\xi_1,\xi_2)\times\left[\xi_1\xi_2(\xi^2-3\beta^2)\cos\alpha b\sin\beta b\; 4\alpha\beta\xi_1\;\xi_2\;\sin\alpha b\cos\beta b\right]\right\}\partial\xi_1\;\partial\xi_2$$

where:

$$\alpha = \sqrt{-\xi_1^2 - \xi_2^2 + \frac{\omega^2}{c_p^2}} \qquad \beta = \sqrt{-\xi_1^2 - \xi_2^2 + \frac{\omega^2}{c_s^2}}$$

and where the wavenumber $\xi = \sqrt{\xi_1^2 + \xi_2^2}$, c_s and c_p are the longitudinal and shear velocities, ξ_i is the wavenumber in the propagation direction, and:

$$D_s = (\xi^2 - \beta^2)^2 \cos\alpha b \sin\beta b + 4\xi^2\alpha\beta \sin\alpha b \cos\beta b$$

Phase velocity can be calculated from guided wave theory [8]. Considering the emitter to be a circular transducer of finite radius a_0, the functions $\bar{F}_1$ and $\bar{F}_2$ are defined as:

$$\bar{F}_1 = \frac{-i\big(a_0 J_1(\xi a_0)\big)\xi_1}{\xi} \qquad \bar{F}_2 = \frac{-i\big(a_0 J_1(\xi a_0)\big)\xi_2}{\xi}$$

where , $J_1(\ \ )$ is the Bessel function of the first kind of order 1. Integrating these equations and transforming into polar coordinates yields to the final displacement in the propagation direction:

$$u_1^s(\omega) = \frac{\pi i \tau_0}{4\mu} e^{i\omega t} \sum_{\xi} a_0 J_1(\xi a_0) \frac{N_s}{D_s'} H_1^{(2)}(\xi r)$$

where μ is a Lame constant, τ_0 the strain generated at the boundaries of the piezo actuator, D_s' is the derivate of D_s (ξ), and $H_1^{(2)}(\ \ )$ is the Hankel function of the second type of order unity and:

$$N_s = 2\alpha\beta \sin\alpha b \cos\beta b + (\xi^2 - \beta^2) \sin\beta b \cos\alpha b$$

The effective diameter of the PZT considered in the propagation model is calculated from the shear lag theory [11]. The theoretical shape of the S_0 mode signal measured at point *p* after propagation from the emitter *m* is expressed by:

$$s_{mp}^s(t) = \int_{-\infty}^{\infty} E_m(\omega) u_1^s(\omega) e^{i\omega t} d\omega$$

where $E_m(\omega)$ is the Fourier transform of an excitation signal $e_m(t)$ at the actuator.

Damping Characterization Based on Guided Waves

A ratio between the maximum amplitude of the simulated signal $s_{mp}^s(t)$, and the maximum amplitude of the measured signal $u(t)$ is first estimated for various distances. The standard deviation between the ratios for various propagation distances is then used as the cost function minimized by a genetic algorithm used for optimization. During the calculation of phase velocity, imaginary part of stiffness parameter is used to integrate damping in the propagation model, as described by:

$$E' = E(1 + i\eta)$$

where *E* represents an elastic modulus of the stiffness matrix and η the associated damping coefficient. The strategy used for the characterization method is presented in Figure 1.

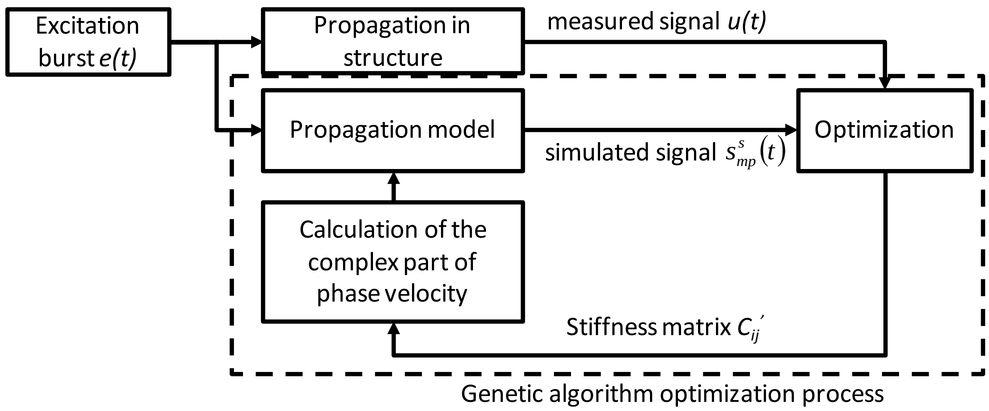

Figure 1 - Characterization method

The strategy is based on reducing the standard deviation between the amplitude ratios of signals measured at various frequencies from the emitter with a theoretical dispersed signal. The minimization algorithm uses the genetic algorithm method because of its simplicity, accuracy and speed of calculation. The termination conditions are the maximum number of iterations, set to 200, and a tolerance of $1\text{x}10^{-4}$ of variation between the results for two successive iterations. In general, one analysis requires 100 iterations.

NUMERICAL ASSESSMENT

FEM Setup

The proposed characterization method is first assessed with FEM by following the characterization methodology to recover the damping coefficient used in the FEM. A 3D FEM has been built using COMSOL 4.2 and a transfer function for the in plane displacement in the frequency domain was calculated between a PZT emitter for a frequency range between 1 kHz and 100 kHz with steps of 1 kHz. Three simulations of an isotropic structure have been performed, each having a different imaginary part of the Young Modulus of 1%, 5% and 10%. Perfectly matched layers (PML) have been used to reduce the size of the model and to avoid boundary reflections. Particular attention is paid to ensure at least 30 elements per wavelength. Numerical simulations were performed on a dual six core Intel XEON 5650 2.67 GHz with 96GB of memory. Computational time for one analysis is roughly 18 hours. The model is presented in Figure 2. Table 1 presents the mechanical and geometrical properties of the FEM.

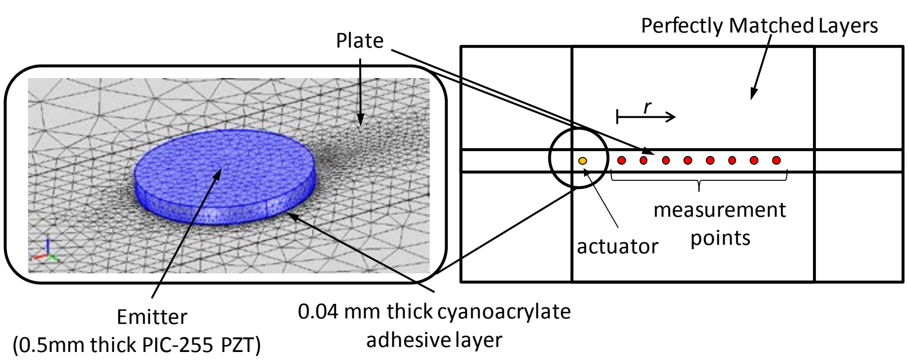

Figure 2 - FEM of a 1mm thick isotropic plate with bonded PZTs

Table 1 - Mechanical properties used in the FEM

Component	Property	Value
Plate	Dimensions (*l*,*w*,*t*)	170x7.5x1 mm
	Elastic modulus *E*	70 GPa
	Damping coefficient *E'*	1%, 5%, 10%
	Density ρ	2700 kg/m^3
	Poisson's ratio v	0.33
Adhesive	Thickness	0.04mm
	Adhesive type	Cyanoacrylate
	Elastic modulus *E*	1.2 GPa
	Poisson's ratio v	0.21
PZT	PZT type	PIC-255
	Thickness	0.5 mm
	Elastic Modulus	60 GPa
	Diameter	5 mm
FEM properties	Number of elements	682 800
	Time to solve (approx.)	18h
	Max element size	0.45 mm
	Number of DoF (approx.)	3409000
	Frequency range	1:1:100 kHz

Results

Time domain signals made of 5.5 cycles bursts are generated and were simulated at each measurement point for various frequencies from the frequency domain transfer function obtained with the FEM. These time signals are then compared with the propagation model to evaluate the damping properties. The damping properties are evaluated with a time signal using only S_0 mode since the propagation model is available in the literature [12]. The boundaries of the explored domain of damping coefficients are between 20% and 0%. Figure 3 presents the comparison between the FEM using 10% damping, the signals simulated using the propagation model with the damping obtained from the characterization method, and theoretical dispersed signals at 80 kHz with a damping coefficient of 0%.

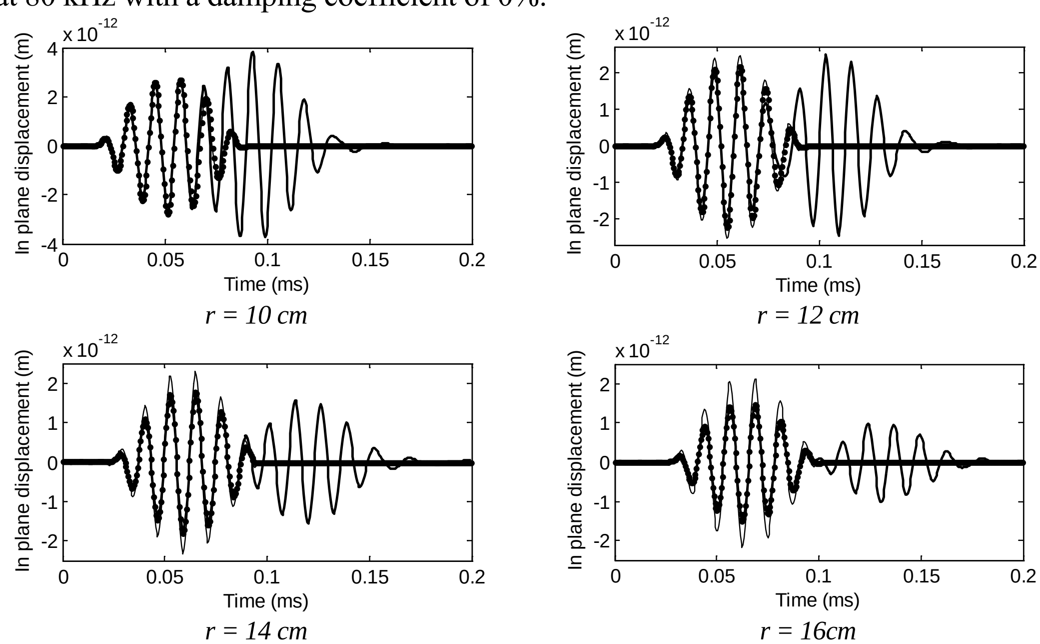

Figure 3 : Signal amplitudes (*solid = FEM, + = propagation model with characterized damping, thin solid = 0% damping*)

The amplitude of the simulated (dotted and thin solid) and measured (thick solid) signals are normalised with respect to the measurement at 10cm in order to better assess the variation in amplitude. An excellent agreement for the S_0 packets is demonstrated by visually comparing the amplitudes of the generated bursts. The peak amplitude is in excellent agreement for all the distances presented. The optimal damping coefficient estimated after convergence for each frequency and model is presented in Table 2 for different frequencies used for the excitation signal.

Table 2 - Estimated damping coefficients

FEM %E'	**Freq.**	**50 *kHz***	**60 *kHz***	**70 *kHz***	**80 *kHz***	**90 *kHz***	**Average**
1%	E'	1.24	0.95	0.74	1.25	0.98	**1.03**
	% Var.	24%	5%	26%	25%	2%	3.0%
5%	E'	4.85	4.93	5.25	4.83	5.12	**4.99**
	% Var.	3.0%	1.4%	5.0%	3.4%	2.4%	0.2%
10%	E'	9.78	9.76	10.40	9.56	10.66	**10.03**
	% Var.	2.2%	2.4%	4.0%	0.4%	6.6%	0.3%

Discussion

For the three damping coefficients modeled, accurate characterization can be achieved. In order to obtain accurate results, proper mode discrimination is required, such that a minimal distance of 10 must be considered. Variations are noticed for low damping structures (1%), which might be impaired by numerical uncertainty. These variations might also be caused by the fact that the propagation model does not consider the dynamics of the emitter.

EXPERIMENTAL ASSESSMENT

Experimental Setup

The characterization approach is implemented for a 2.33 mm thick $[0]_{16}$ CF-EP plate with the properties presented in Table 3. The structure is instrumented with a 5 mm PIC-255 PZT actuator bonded using cyanoacrylate adhesive. A signal generator (HP 33120A) with a sampling frequency of 15 MHz is used to generate the burst and an acquisition board (NI PCI 5105) is used to record signals with a sampling frequency of 60MHz. A ProduitSon UA-8400 high voltage and large bandwidth amplified the excitation signals to 200 VPk. Bursts of 5.5 cycles at frequencies between 50 and 200 kHz are used as input signal and measured at distances from 1 cm to 10 cm of the emitter. Figure 4 presents the experimental setup. The in-plane displacement model is used to model the out of plane displacement as a first approximation to demonstrate the repeatability of the approach to evaluate the same damping over multiple frequencies.

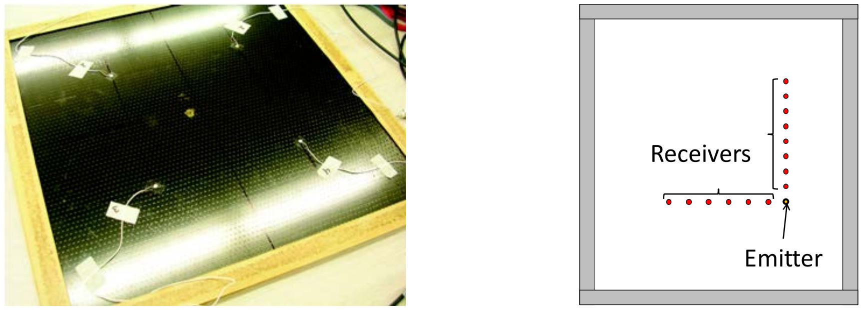

Figure 4 - Experimental setup

Table 3 - Properties of the experimental setup obtained using [4]

Component	Property	Value
Plate	Dimensions (*l*,*w*,*t*)	51x51x0.23 cm
	Longitudinal modulus (*El*)	115.75 ± 14 GPa
	Transverse modulus (*Et*)	8.55 ± 0.39 GPa
	Shear modulus G_{12}	3.87 ± 0.2 GPa
	Poisson's ratio ν_{12}	0.28 ± 0.05
	Density ρ	1488 kg/m^3

Results

Figure 5 presents the comparison between the experimental signals at 50 kHz simulated using the propagation model with the damping obtained from the characterization method, and theoretical dispersed signals with a damping of 0%. The optimal damping coefficient estimated after convergence for each frequency is presented in Table 4 for different frequencies used in the excitation signal.

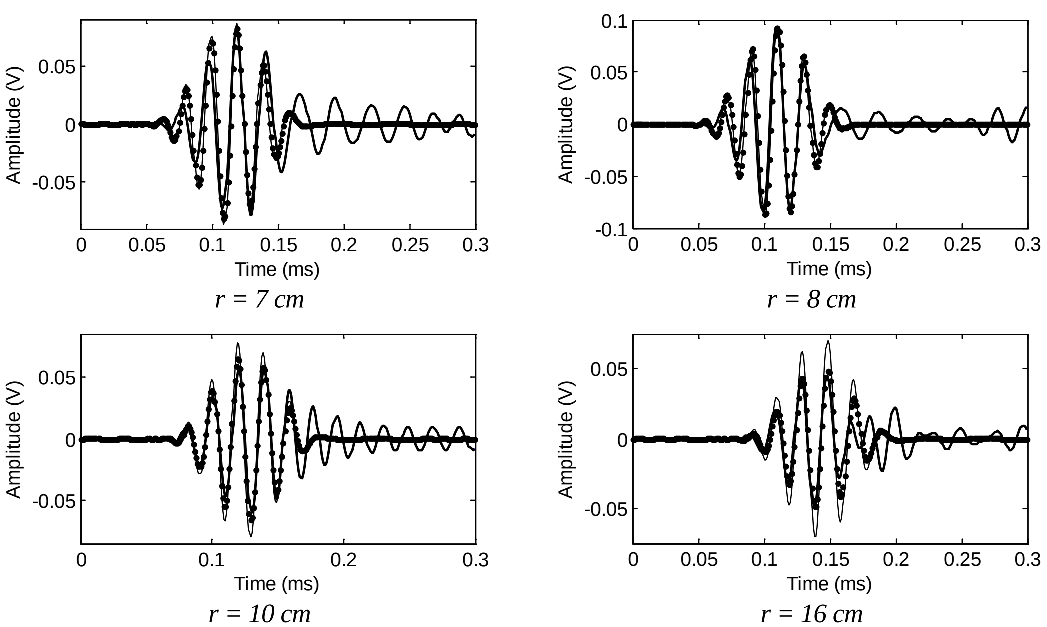

Figure 5 - Signal amplitudes in the fiber direction (solid = experimental, dot = propagation model with characterized damping, thin solid=0% damping)

Table 4 - Estimated damping coefficients

Freq.	50 *kHz*	75 *kHz*	100 *kHz*	125 *kHz*	150 *kHz*	Average
E_L' (%)	3.48	2.15	1.85	2.03	1.69	2.40 ± 0.71
E_T' (%)	6.75	6.92	5.57	3.52	6.41	5.83 ± 1.39

Discussion

The experimental results demonstrate that accurate amplitude is predicted with the characterized damping, as shown in Figure 5. The numerical results show that the damping coefficient is higher in transverse to the fiber direction. In order to better assess the damping of the structure, the theoretical equations of the out of plane displacement should be used for further work. Also, the amplitude variation obtained is in a good agreement with the experimental measurement. The accuracy of the propagation model could also be improved by considering the dynamics of the actuator.

CONCLUSION

This paper presents a method to evaluate the damping properties of both an isotropic and a composite plate-like structure using guided wave propagation. For known geometrical and mechanical properties, the damping coefficients are evaluated using a characterization method. The FEM assessment demonstrates the potential of the approach to evaluate accurately the damping properties of the structure within 5% of the exact damping. The experimental analysis demonstrates the potential of the approach to estimate accurately the amplitude drop of the signals. Ongoing work aims at developing and implementing the out of plane displacement equations, integrate the dynamics of the adhesive and PZT, and integrating the method to imaging approaches in order to increase the autonomy of imaging methods.

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