CIVA SHM for guided wave simulation: damping model and absorbing boundary layers

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Abstract Simulation plays an increasing role in industrial applications as it allows to reduce times and costs associated to several tasks, among which design and certification. It is the case in particular for guided wave SHM, for which many parameters may affect the system performances and may be costly to explore. Typical examples are: uncertainties on material parameters and sensors, varying defect positions and geometries, environmental and operational conditions like temperature, static load or sensor aging. Simulation solutions hence need to be fast enough to enable large simulation campaigns, representative of all expected conditions, while showing a good accuracy with respect to the modeled effects. The SHM module of CIVA has been designed for this purpose. It uses a transient high-order spectral element method coupled with a parametric description of the geometry and its features, such as sensors, stiffeners and defects. Relying on the so-called mass lumping method while performing unassembled stiffness operations in parallel, fast computations with low memory consumptions are obtained. Two new features have been added to increase the accuracy of simulation and its computational performances, namely damping models and absorbing boundary layers. Damping models play an important role in accurately predicting the propagated field, in particular for composite materials in guided wave SHM applications. However, they come at an increasing cost. We will show in this presentation three available models, namely Maxwell, Zener and Kelvin-Voigt, which may be used based on a trade-off between needed accuracy, knowledge of the damping laws, and computational cost. Validation results will also be presented. In parallel, absorbing boundary layers enable to restrict the size of the simulated domain, thus limiting the computational cost. Indeed, these layers damp waves going outward with a small reflection at the interface between the physical domain and the absorbing one. They hence enable to perform the computations in a limited physical domain without introducing boundary reflections. The length of these layers is chosen automatically based on the wavelengths of the propagating modes. These layers, their associated cost as well as comparisons between simulations with and without them, will be presented.

Keywords: simulation; guided waves; damping; boundary conditions

Introduction

Ultrasonic guided waves have been a subject of interest for SHM for several years, as these waves can propagate over large distances while being sensitive to small defect, enabling sparse, cost efficient sensor networks. These waves propagate in waveguides like plates, pipes or rails, which are of interest for many domains like transport or energy. However, acquired signals and their processing are also sensitive to several parameters such as temperature, static strain or sensor coupling and aging, not to mention parameters of potential defects. It is hence necessary, to design and assess the performances of an SHM system, to consider various parameters. The associated costs hence become prohibitive as several instrumented samples need to be considered.

To circumvent this issue, simulation enables to limit the costs by generating preliminary data to determine relevant parameters and their corresponding effects. Models are then needed for these parameters with a reasonable computational cost to perform large parametric studies or the generation of large databases to train models.

Several simulation strategies have been designed for guided waves over the years: semi-analytical methods are very efficient when large propagation distances in perfect waveguides are considered [1, 2], and they can be hybridized with local finite element computations [3, 4] to take into account local perturbations like defects. Similarly, local interaction simulation approaches (LISA) [5] have been developed to use finite elements in the vicinity of perturbations while relying on finite differences for propagation at a smaller computational cost.

As the configuration becomes more complex, with several perturbations associated to the waveguide, fully numerical computations are needed to accurately and efficiently simulate wave propagation. Two main approaches have been considered recently because of their good performances. Finite elements using GPUs [6] enable limited computation times thanks to highly parallelized computations. However, they require specific hardware. On the other hand, transient spectral element methods [7, 8, 9] enable low cost computations on standard hardware.

Models are also needed to take into account the varying parameters: environmental and operational conditions like temperature [10] and mechanical loading [11]. Note that these parameters may impact different aspects of the model, for example transducer models and wave propagation in the host structure. Among them, the viscous behavior of the material is important to accurately simulate the signals [1], especially for composite materials [12]. Several damping models have been proposed over the years, among which one can cite Rayleigh damping [12], the hysteretic model [13] and the Kelvin-Voigt model [5] as being the most frequently used in this context. The model choice will lead to different behavior, especially in terms of frequency dependency of the damping. This choice may also have an impact on computational performances, especially when considering transient numerical methods.

In the SHM module of CIVA [8], transient spectral elements are used. Three damping models have been introduced, as detailed in [14], and their impact for the simulation of guided waves will be discussed in the following. Using this numerical method leads to simulations in a bounded domain, which may introduce unwanted edge reflections. To limit their impact, an extended domain may be considered at an increased computational cost. Another possibility is to introduce absorbing boundaries like Perfectly Matched Layers [15]. These layers are however unstable in the guided wave context. Stable alternatives have been proposed in the literature [16, 17], and we will present here the formulation used in CIVA.

The first part of the paper will recall the principle of the used transient spectral elements, before addressing the damping models and their validation in the second part and finally the absorbent boundary layers in the last part.

1. Description of the used transient spectral elements

The SHM module of CIVA relies on a parametric description of subdivisions, named macro-elements, of the geometry. These macro-elements are linked to the features of the configuration such as stiffeners or sensors. By doing so, three dimensional complex geometries can be discretized in space using high-order spectral elements based on the tensorial product of one dimensional elements. The high order discretization hence leads to a reduced number of degrees of freedom compared to conventional finite elements for a given precision. In addition, an explicit time scheme is used, for which the mass matrix needs to be inverted at each time step. However, using spectral elements, this matrix is diagonal, drastically reducing the associated cost. Finally, as the inverted matrix is diagonal, the stiffness matrix does not need to be assembled to perform the computation, reducing even further the computational and memory costs. For a more detailed description, the interested reader is referred to [7, 8]. There are two main drawbacks to this strategy: first, the geometry needs to be parametrized. Parametric description of relevant features are hence being continuously added to the software to enable an increasing simulation complexity. Second, as the time scheme is explicit, simulation time steps are strongly dependent on the mesh and the viscoelastic parameters, as we will see in the next section.

2. Damping models

2.1 Overview of used damping models

Three damping models are considered in this study, which can all be parametrized using a stiffness matrix C^*, a viscosity matrix D^* and a reference frequency ω^* at which C^* and D^* have been determined. For more details, the reader is referred to [14]. The main differences between those models are, from the physical point of view, the dependency of the attenuation law, which is the imaginary part of the wavenumber, with respect to the frequency and, from the computational point of view, the added cost for time-explicit spectral element schemes. They are:

- The Maxwell model, which assumes a constant behavior of the attenuation law with respect to the frequency. It has only a limited additional cost compared to the inviscid case: double unknowns need to be considered, leading to an increased memory cost, and the time step is smaller than in the inviscid case, for a given configuration, but preserving a linear dependency with respect to the mesh fineness.
- The Zener model,which assumes a locally linear attenuation law, in the vicinity of the calibration frequency. Its additional cost is bigger than the Maxwell model as double unknowns need to be considered, the time step is smaller than in the Maxwell case, with a linear dependency with respect to the mesh fineness, and each time step has roughly a doubled computational cost due to two applications of the stiffness matrix.
- The Kelvin-Voigt model, which assumes a quadratic attenuation law. This model is the most expensive: although there is no need for double unknowns, two stiffness matrix applications are needed and the time step has now a quadratic dependency with respect to the mesh fineness.

Note that the time step also depends on the product $C^* D^{*-1}$. For small viscosity values, which is the case for most guided wave applications, the time step for the Kelvin-Voigt model will depend linearly on this product while it will be negligible for the two other models. Because of that, the time step decrease linked to the use of the Kelvin-Voigt model may be less important.

As already mentioned, among these models, the most used for guided wave propagation in viscoelastic media is the Kelvin-Voigt model, which has been shown to allow good matches with experimental data [5]. However, its cost can severely degrade computational performances for a limited improvement in accuracy, especially as damping parameters are hard to measure in most applications.

2.2 Validation

Computations have been performed on the case described in [5]. We consider a composite panel composed of 12 0.125 mm thick plies of CFRP, all plies being in the 0° direction. Cor-

Stiffness coefficients	E_{11} (GPa)	$E_{22} = E_{33}$ (GPa)	$\nu_{12} = \nu_{13}$	ν_{23}	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)
Values	147	9.8	0.41	0.69	5.3	3.31
Viscosity coefficients	D_{11}	D_{22}	D_{33}	D_{44}	D_{55}	D_{66}
Values (Pa.s) $\omega^* = 1$ rad.MHz	328.6	525.7	525.7	722.8	394.3	394.3
Values (Pa.s) $\omega^* = 2\pi.0.075$ rad.MHz	155.2	248.1	248.1	341	185.8	185.8

Table 1. Material properties of the considered CFRP plate.

responding material parameters are given in table 1. Note that in [5] a Kelvin-Voigt model without calibration frequency is used. The damping matrix in this case can be expressed as

$$D = \frac{1}{\omega^*} D^*,$$

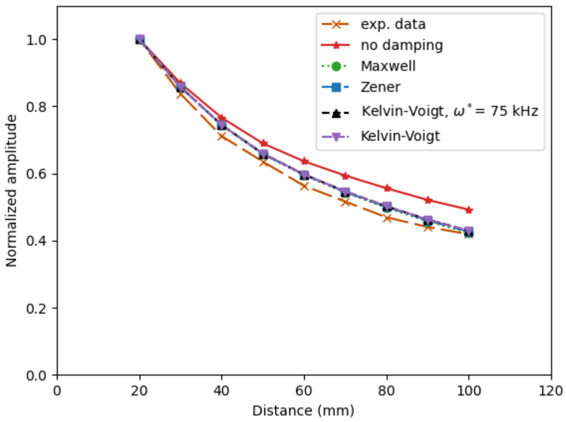
where D is the matrix as used in [5], and D^* is the matrix used as an input in our simulations. As the Zener model is only locally linear, it is necessary for this model to define the viscosity matrix at the frequency of interest to obtain the expected results. We hence multiplied the values of [5], corresponding to a unitary calibration frequency in our case, by $1/(2\pi.0.075)$ to obtain the corresponding values for a 75 kHz calibration frequency, as this center frequency is used in the following.

To avoid interactions between direct wave packets and reflected ones from the edges of the plate, it is a square of side 500 mm. An emitting piezoelectric patch of diameter 12.8 mm is at the center of the plate. A 3 cycle Hann burst of center frequency 75 kHz is used as excitation. To mimic measurements from the laser Doppler vibrometer at normal incidence, normal displacement is extracted from the simulation every 10 mm along 0°, 45° and 90°, starting at 20 mm from the emitter. Simulations are run without and with damping, for the three models with corrected viscosity matrix for a calibration frequency of 75 kHz and, in addition, considering the Kelvin-Voigt model with the initial viscosity coefficients and an unitary calibration frequency. The maximum of the envelope of the corresponding signals is extracted and plotted in figure 1. In addition, the experimental data from [5] are added for comparison. Data are normalized with respected to the maximum of each configuration.

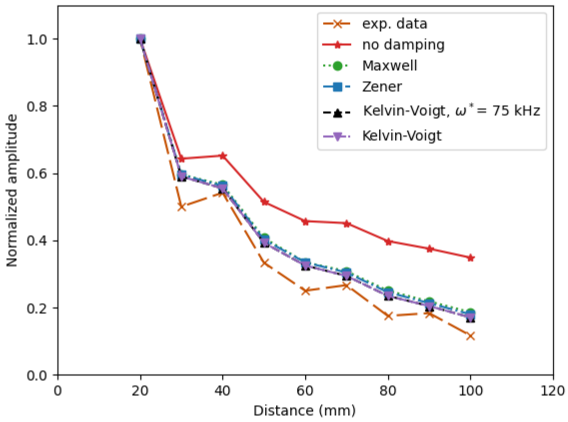
We can see in these plots that all models give very similar results, with both parametrization of Kelvin-Voigt giving exactly the same results as they are equivalent. This is expected: even though the underlying damping behavior of the material is differing between the models, as the frequency bandwidth of excitation signals usually used in SHM is limited, the difference in terms of computed wavefield is actually small.

To get a more detailed comparison of the computed signals, we plotted in figure 2 the signals corresponding to a propagation distance of 100 mm in the three directions. As expected, both simulations using the Kelvin-Voigt model are superimposed. We can however see slight differences between the models, especially in the 45° and 90° for which the damping is more important. We can see indeed for the second wave packet, starting approximately at 60 µs for the 45° direction and 80 µs for the 90° direction, that the amplitude of the Kelvin-Voigt cases are smaller for the first oscillations but higher for the latest ones. This is directly linked to the dispersive behavior of the guided mode, with higher frequencies arriving first in this case, and lower frequencies later. It is hence coherent with a damping increasing with the frequency. Slight phase shifts between models are also visible, which are also expected.

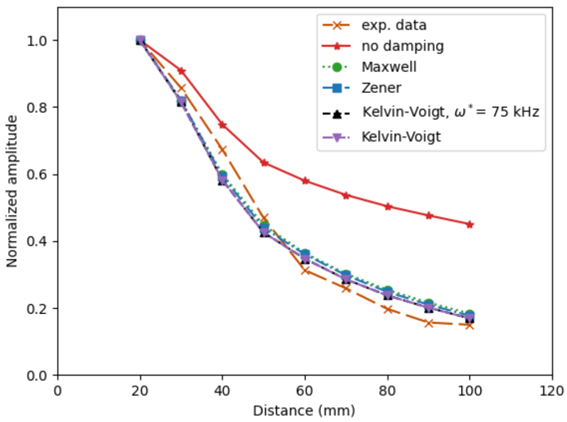
Finaly, regarding the computation performances, computations without damping took 4 min 38 s without damping, 6 min 8 s with the Maxwell model, 9 min 14 s in the Zener case and 13 min 9 s and 13 min 5 s for both Kelvin-Voigt computations. All computations were performed on the same computer with an 18 core Intel© Xeon W-2295 processor of fre-



(a) *0°*



(b) *45°*



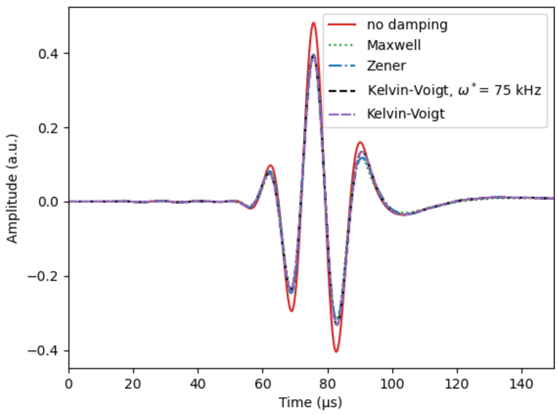
(c) *90°*

Fig. 1. *Comparison of normalized amplitudes of signals at various propagation distances with and without damping.*

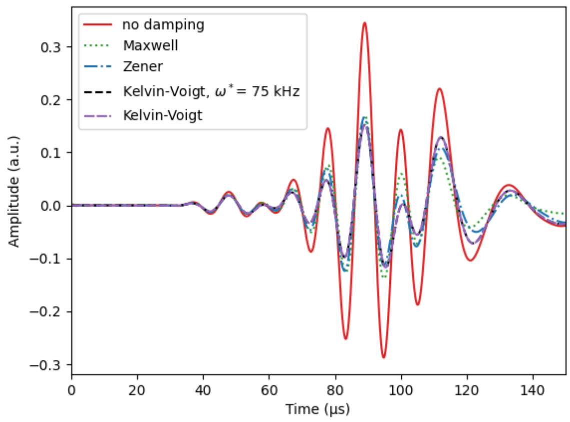
quency 3 GHz. We see in this case that, as expected, the different models have very different impacts on the computation performances. Given the small difference in simulated signals but the large impact on computation performances, considering other models than Kelvin-Voigt for such simulations may indeed significantly reduce the computation burden, enabling large parametric studies which would otherwise be too costly.

3. Absorbing boundary layers

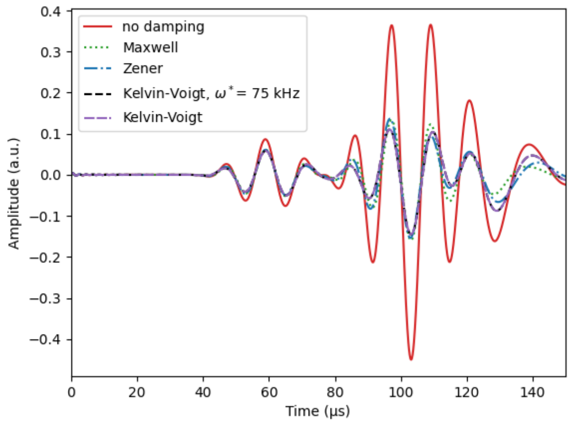
In addition to accounting for physical damping, viscosity models may also enable to restrict the computation domain while introducing negligible boundary reflections, reducing further the computational burden. Here, absorbing boundary layers are deduced from the Perfectly Matched Layers (PML) system [15] by considering the same damping along all directions. In practice, this leads to a stable system, which is not guaranteed for PMLs, at the cost of small reflections at the interface between the physical domain and the boundary layer. These layers are named hereafter Absorbing Layers (ALs). Note that the obtained system is close to the Maxwell damping model and the one described in [17]. To avoid reflections at the end of the layer, its size is automatically computed based as two times the maximum wavelength of the configuration. As the mesh cell size depends on the minimum wavelength, the gain in computation performance strongly depends on the ratio between these two quantities. Note that, in most configurations, such layers will hence lead to better performances for higher



(a) *0°*



(b) *45°*



(c) *90°*

Fig. 2. *Comparison of extracted signals for a propagation distance of 100 mm.*

excitation frequencies and narrow bandwidth, as the ratio between minimum and maximum wavelength will increase.

The use of such absorbing layers is illustrated in the same configuration as before, without damping. Three cases are considered: a plate side length of 500 mm (same as before) without ALs, a side length of 150 mm with ALs and the same without them. For smaller plates, the emitter is 20 mm away from the limit of the physical computation domain in both directions. A snapshot of the computed field in the case with boundary layers is plotted in figure 3. We see qualitatively that the wave packets are indeed absorbed by the layers.

Signals corresponding to various propagation distances in the 90° direction are plotted in figure 4. We see that the signals without AL in the extended domain and with AL in the small domain give the same results, whereas the edge reflection can be clearly seen in the small domain without AL. Computing the residual of the two restricted configurations with respect to the extended domain, the maximum amplitude using ALs is of 3% while it is of 84% without them.

Finally, regarding the computation time, the computation in the extended domain took 4 min 38 s while the computation using ALs took 2 min 52 s, significantly reducing the computation time in this case.

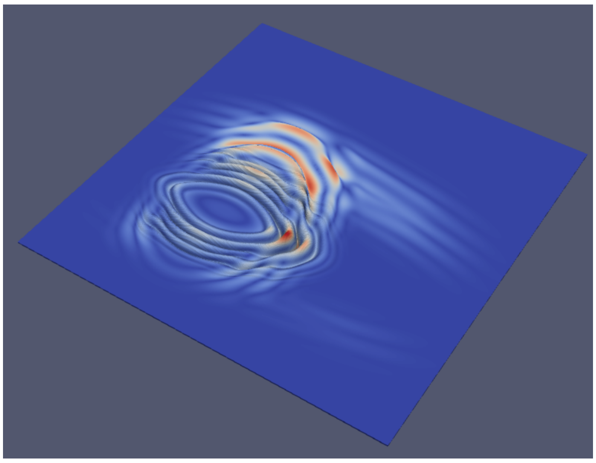


Fig. 3. *Snapshot of the simulated wavefield with absorbing layers.*

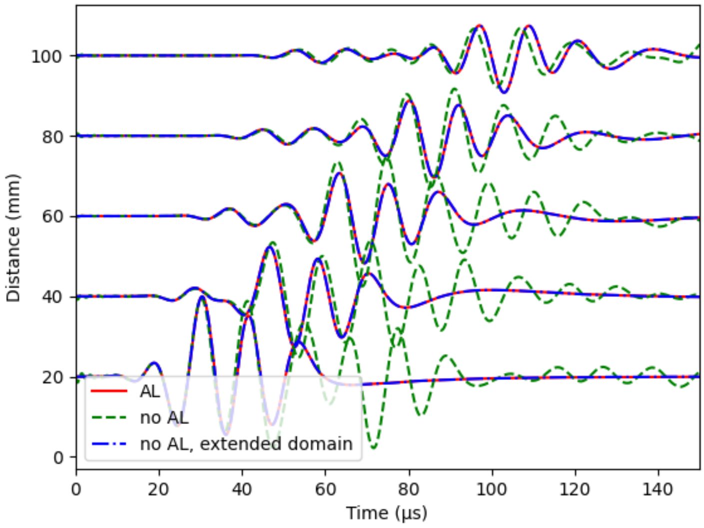


Fig. 4. *Simulated signals at various propagation distances for a propagation at 90°.*

4. Conclusions

We have shown in this paper the use of damping models coupled with transient spectral finite elements in the SHM module of CIVA. Although the Kelvin-Voigt model is usually considered for guided wave simulations, its impact on performances in this case may prevent its use for large scale simulations. Other models such as the Maxwell model give similar results for such applications, due to the limited bandwidth, with a limited additional costs. Furthermore, as viscosity coefficients are hard to determine, the potential added accuracy obtained from chosing a specific model such as Kelvin-Voigt may be below the uncertainty associated with the used parameters.

In addition, absorbent boundary layers are available to restrict the computation domain and the associated cost. As the length of the layer depends on the biggest wavelength of the configuration, the performances strongly depend on the use case. In particular, specific meshing of the layers will be studied to further reduce the associated computational cost.

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