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ScienceDirect

Physics Procedia 70 (2015) 532 – 536

Physics Procedia

2015 International Congress on Ultrasonics, 2015 ICU Metz

Influence of the numerical dispersion effects in the modelling of ultrasonic measurements

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Abstract

The modern structures in aerospace, transport, wind energy and other industries contain components manufactured of composite materials. One of the advanced techniques used for inspection and monitoring of such structures are based on the application of guided ultrasonic waves. Numerical simulation is one of the most efficient tools enabling adequate interpretation of a signal. However, the necessity to relate the sampling steps in time and space domains with frequency and wavelength of the ultrasonic waves propagating within the object under investigation often leads to unacceptably long simulation time. Employment of coarser meshes tends to create additional problems caused by the numerical dispersion effects. It leads to the distortion of the shape of the simulated signal and mismatches against the experimental results.
The objective of this work was to investigate the numerically caused distortions in simulated ultrasonic waves and to develop the technique enabling to minimize their influence. The analysis has been carried out by investigating the propagation of wideband ultrasonic waves in materials with known elastic properties by using the finite element model. The calculated signals have been used for the estimation of the propagation velocity, which has been compared against the corresponding wave velocities obtained by the analytical formulae and against signal velocities measured experimentally.
As a result of the investigation, the rules enabling to determine a well-balanced set of modelling parameters have been developed. It was demonstrated that the models developed on the base of this set of parameters enable to reduce the numerical dispersion errors, as well as, the simulation time.

Peer-review under responsibility of the Scientific Committee of ICU 2015

Keywords: Lamb wave; dispersion; group velocity; simulation; experiment; finite element modelling

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Peer-review under responsibility of the Scientific Committee of ICU 2015
doi:10.1016/j.phpro.2015.08.010

1. Introduction

Ultrasonic guided waves are widely used in non-destructive testing (NDT), in pursuance to identify defects in different materials or for monitoring the state of structures. For the identification of defects usually the pulse – echo method is used where the Lamb waves are generated by piezoelectric, electromagnetic acoustic transducers (EMATs), etc. (Zhai et al., 2010). The advantage of the guided waves is their ability to propagate relatively long distances. In this way they enable the large coverage during inspection. However, the investigation of guided waves propagation in large structures is complicated experimentally, as well as, by employing computational techniques. The commonly used modelling and simulation approaches are based on finite element method (FEM) or on its modifications. The finite element modelling enables to investigate the guided waves propagation in a structure, as well as the interactions of the waves with different kinds of defects or non-uniformities. The key problem in the FEM investigation of wave propagation is the necessity to relate the dimensions of finite elements to the shortest wavelength component of the propagating signal. Very small space sampling steps require small time sampling steps in order to assure numerical stability and accuracy. The signals propagating in planar elongated structures are usually composed of multiple wave modes. The space sampling steps have to be related to the shortest wavelength (the slowest wave mode). In case of large structures under investigation huge computational resources are necessary. Additional difficulty in simulation of waves occurs due to numerical dispersion. This means the deterioration of the shape of the propagating signal due to small errors of propagation velocities of different modal components of the signal. The numerical dispersion is inherent inaccuracy of all discrete models of wave propagation rather than is related to any physical phenomenon. This means that even in the simulation results of bulk ultrasonic waves in homogeneous media this fictitious dispersion can be observed, though it does not exist in reality.

Several numerical dispersion compensation techniques are presently available. The Window Fourier transform (WFT) is a unitary time-frequency transformation that produces a flexible sampling of the time-frequency domain. It has been shown by De March et al. (2009, 2010) how the WFT can be efficiently used to extract the dispersive characteristic of Lamb waves in the time-frequency plane. Rayleigh-Lamb equations constitute the starting point for most investigations and permit analysis of phase velocity as a function of frequency and plate thickness (Hayward and Hyslop (2006), Victorov (1967)). Lin (2012) proposes to solve this problem in Pseudo-spectral time-domain (PSTD) method using digital filtering. Sun (2005) Sun investigates numerical dispersion and loss for Yee's FDTD in lossy media. Later investigations in this direction extend the Moss and Teixeira (2012) by studying the numerical dispersion effects for the FDTD method in anisotropic and layered media. The method allowed investigating scattering from objects in complex media with weaker responses. Banks et al. (2006) studied the stability properties and the phase error present in a finite element scheme for Maxwell's equations coupled with a Debye or Lorentz polarization model. The article provided the first step in the construction, implementation and analysis of finite element schemes for modelling dispersive wave phenomenon. Zyserman and Santos (2007) analysed the numerical dispersion properties of FE dynamic models of fluid saturated porous elastic solid (a Biot medium) in two-dimensional case at low frequencies. The study was performed by constructing and analyzing analytical and numerical dimensionless dispersion relations, and by evaluating derived quantities such as dimensionless phase and group velocities and dimensionless attenuation.

Weckner and Brunk (2002) investigated the numerical dispersion problem analytically. They obtained the cut-off-frequencies, however, could not explain the physics of their existence. Most commonly on this issue worked Murthy et al. (2004). They developed a simple but effective method for reducing numerical dispersion in finite element solutions of time-harmonic wave propagation problems. The only disadvantage was that the method worked only with square elements, and it remains unclear how will be with general two-dimensional and three-dimensional models.

However, most investigations of the dispersion compensation techniques did not reveal the dependence of the extent of manifestation of numerical dispersion effect on the size of sampling steps in time and space domains. The objective of this work is to investigate the dependence of the numerical dispersion on the size of sampling steps and to find their optimal values.

2. The set-up of numerical modelling

The numerical experiments have been carried out by investigating the ultrasonic bulk wave propagation in the steel plate of dimensions: 80 x 50 mm. The elastic properties correspond to the steel AISI 630. The 2D model was used. The ultrasonic waves were generated at one side of the sample (Fig.1) by attaching force possessing both tangential and normal to the surface components. In this case two types of the waves are excited: longitudinal and shear. The excitation waveform was the rectangular pulse of duration 40ns. The harmonic components of rectangular pulse cover rather wide frequency bandwidth. It is important in this research as the intensity of manifestation of numerical dispersion increases with frequency. The central frequency is 12.5MHz. The propagation of the waves was investigated along central line of the sample. The simulation has been carried out using ANSYS finite element software. Several experiments have been carried out with different sampling steps in space domain. The sampling steps used are (0.005;0.01;0.02;0.04mm). The wavelengths of shear and longitudinal waves have been estimated by assuming propagation velocities 3200m/s and 5900m/s correspondingly. In each case the longitudinal and shear components of particle velocities along central line have been collected and analyzed.

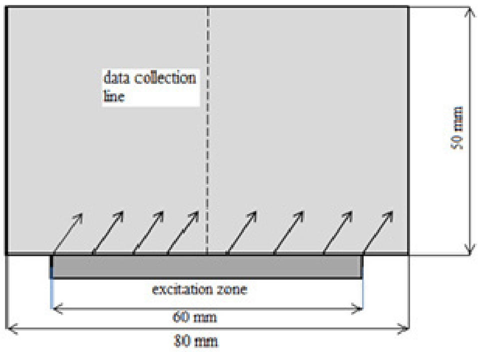

Fig. 1. The 2D model of steel sample under investigation.

3. The results of modelling

The obtained B-scan images of the longitudinal and shear components of particle velocities in the steel sample are presented in Fig.2 (a) and (b). It can be noticed that the B- scan image of the longitudinal component is much clearer as the longitudinal waves are fastest ones and the pattern of their propagation is not disturbed by other modes. On the contrary, the pattern of shear waves is slightly disturbed by various reflections of faster longitudinal waves. In both cases, significant influence of the numerical dispersion can be clearly observed. The pattern of the dispersion curve can be observed up to relatively high frequencies. In order to estimate the character of the observed dispersion the B-scan data have been converted from space-time domain into phase velocity - frequency domain by using 2D Fourier transform. Obtained images of dispersion curves are presented in Fig.3 (a) and (b). The phase velocities in the images correspond to the white pattern. The numerical dispersion exhibits different tendencies for different wave types. For longitudinal waves the dispersion is higher than for shear waves due to shorter wavelengths. In order to compare the dispersion curves obtained at different refinements of the finite element mesh the obtained patterns were approximated by higher order polynomials. Obtained dependencies are presented in Fig.4 (a) and (b). It can be observed that the numerical dispersion curves are strongly dependent on the mesh size. The observed higher frequencies fit well within theoretical limits corresponding to two elements per wavelength. From the presented dispersion curves it may be stated that the sampling is space domain should be approximately 20 elements per wavelength. So, in the case of finest mesh (0.005mm) the frequencies up to the 60MHz can be analyzed. However, at such frequencies the phase velocity is reduced quite essentially by numerical dispersion and therefore the waveforms of the signals will be distorted. On the other hand, it can be seen that with the coarser finite element mesh

(0.02mm) the numerical dispersion is absent even for wider frequency bandwidth close to 80MHz. The mesh provides only ~4 elements per wavelength. The similar character can be observed in the case of shear waves also when the more course finite element mesh gives stable phase velocity compared to the mesh with smaller element size. Of course the optimal size of the mesh slightly differs for longitudinal and shear waves due to different wavelength, however it is not the finest one.

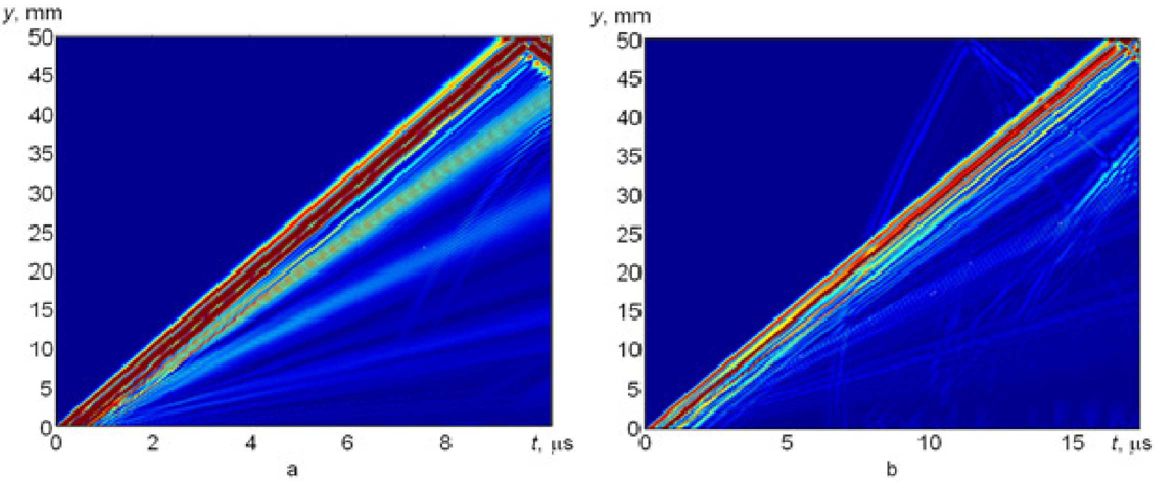

Fig. 2. (a) The B-scan image of the longitudinal wave in steel sample, finite element mesh size 0.005 mm, (b) The B-scan image of the shear wave in steel sample, finite element mesh size 0.005 mm.

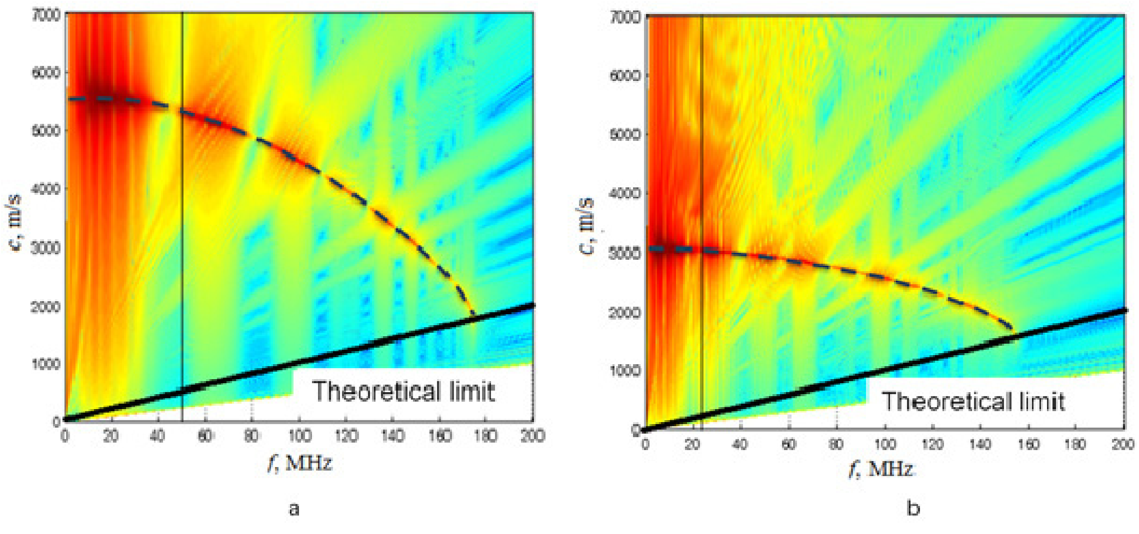

Fig. 3. (a) Dispersion curve of the longitudinal waves, finite element mesh size 0.005 mm, (b) Dispersion curve of the shear waves, finite element mesh size 0.005 mm.

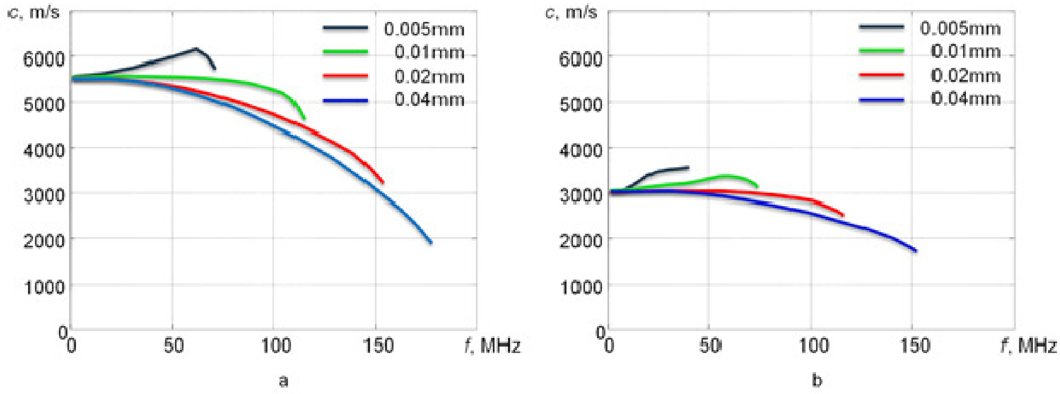

Fig. 4. (a) The numerical dispersion curves of longitudinal wave obtained in simulation using different size of finite element grid, (b) The numerical dispersion curves of shear wave obtained in simulation using different size of finite element grid.

4. Conclusions

On the basis of investigations carried out it is possible to conclude that the oversampling in space domain can lead to the essential increase of the numerical dispersion and to corresponding distortions in the waveforms of the signals. In order minimize the influence of numerical dispersion the size of the finite element mesh should be optimized. It is complicated to set optimal size in advance as it depends not only on the waves under analysis, but also on the time integration scheme used during the modelling. It appears that the best way to optimize the mesh is to carry out the numerical experiments similar as described in this paper. The optimal size of the mesh not only enables to reduce distortions caused by numerical dispersion, but enables to reduce the required computational resources.

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