Frequency and Time Domain Analysis of Guided Waves for Damage Detection

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ABSTRACT

Guided waves have been shown to be a very useful approach for damage detection. Their interaction with inhomogeneities, holes, cracks, delaminations or other defects present in the structure carries important information and can reveal the type and extent of the damage itself. Furthermore, depending on the nature and size of the damage to be monitored, an appropriate mode and wavelength can be used.

Explicit algorithms are used to numerically simulate these interactions giving accurate predictions of what is obtained experimentally. However, the selection of the proper mode and wavelength to be used is strongly dependent on the nature and dimension of the defect and it often requires quite long computational times, as well as a tuning process that can identify the appropriate characteristic of the ultrasonic wave for each defect. Structures of a certain complexity and extent may contain defects of various nature and size and therefore a significant number of analyses may be required: depending on the specific problem, it is necessary to use more than one excitation pulse at difference frequencies and the time-domain analysis needs to be carried out more than once with a further increase of computational costs. Conversely, guided waves in the frequency domain can be used for the same class of problems and may offer some advantages in terms of computational time saving, especially in the case of a multi-damage problem for which a multi-frequency excitation is required. In this paper the numerical solution in terms of frequency response functions (FRF) of the guided waves problem is demonstrated to be an alternative and efficient approach to the time domain analysis. Moreover, the time domain solution can be reconstructed from the FRF data for any input frequency and waveform. The time domain solution reconstructed from the FRF data are compared to solution directly obtained in the time domain. Subsequently a damaged structure will be considered to demonstrate again the efficiency of the FRF approaches. Finally, the advantages and limitations of time and frequency approaches are discussed.

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INTRODUCTION

Solving the GW problem in the time domain (TD) either numerically or experimentally gives detailed information about certain defects or damage inside a structure, but it may require a big effort if many frequencies are required, as in the case of large structures with multiple damage of different sizes and locations [1].

Working in the frequency domain (FD) is generally more efficient, but it is hard to capture transient phenomena occurring over short time periods [2]. It is possible to indirectly assesses the structural response through transfer functions, but further analysis is required to determine stresses, displacements, and accelerations.

To take advantage of both the TD and FD best features, the faster solution in the FD can be directly used for damage localization and the TD solution can be eventually reconstructed from the frequency domain analysis (FDA) for a more accurate damage detection. This second step could be performed without calculating the structural response with transient analysis at each source frequency that requires multiple calculations (one for each source waveform and frequency). Once the frequency response function (FRF) is calculated in a given frequency range, the transient TD response can be immediately reconstructed at any frequency of the range and for any waveform.

In many past works the authors presented a damage detection approach based on the combination of low frequency vibrations (statistical Damage Indices) and ultrasonic waves [3]. The proposed approach thus makes it possible to identify very small areas of damage with a high level of reliability.

TIME AND FREQUENCY DOMAIN SOLUTIONS

The low frequency vibration-based analysis is capable to identify widespread damage within the structure from a large dataset collected by a network of distributed sensors and actuators in relatively complex structures.

The analysis of the waveform signals of propagating GW provides more detailed information on the location and nature of smaller defects from a waveform data set provided by the same network of distributed sensors and actuators [4].

Time and frequency domain analysis (TDA and FDA) are two fundamental techniques employed to evaluate the dynamic behavior of a system, each offering advantages in certain applications. Among the other advantages TDA can capture transient and nonlinear behaviors and directly evaluates the structural response calculating stresses, displacements, and accelerations. However, TDA involves high computational cost for complex structures, long simulation periods and a limited frequency resolution, as it may not provide sufficient frequency resolution for analyzing specific frequency components of the wave spectrum.

FDA is generally computationally efficient, suitable for the analysis of large structures or long-term wave conditions, provides high frequency resolution, making possible detailed analysis of specific frequency components of the wave spectrum. Furthermore, it requires linear relationship between input force and structural response, that may not be valid in certain conditions; it can not capture transient phenomena and it indirectly assesses structural response through transfer functions, requiring further analysis to determine stresses, displacements and accelerations.

For the above mentioned characteristics, the selection of the approach depends on the specific requirements and objectives of the problem to be solved. TDA is preferred when transient behavior, nonlinear interactions, or direct structural response assessment are crucial, while FDA is preferred for spectral analysis and frequency-dependent structural response.

We can conclude that TDA and FDA are complementary techniques rather than competing ones and they may be both employed to obtain a more comprehensive understanding of certain dynamics problems.

TRANSIENT AND FREQUENCY RESPONSE ANALYSES

A layered plate has been considered for the numerical analyses in both the time and frequency domains. The LS-DYNA transient explicit solver has been used to evaluate the guided waves propagation in the time domain, while the frequency response analysis has been performed with the Simcenter Nastran solver.

Although the plate has been modeled as a multilayer laminate to perform the subsequent analyses considering a delamination in the thickness, the material used is a standard aluminum alloy, which does not affect the generality of the approach also valid for composite material laminates.

Both the TD and FD models are realized with 2D plane strain elements. The plate section is 1m long and 3 mm thick. The Young modulus is 70 GPa and the Poisson ratio 0.3. The load is applied in the center of the plate. In the example showed, a time domain analysis has been carried out with a 4.5 sine cycles source waveform with a central frequency of 200 kHz in a Hanning window. The frequency response has been calculated for a constant unit force in the frequency range 0-2 MHz, as showed in Figures 1 and 2.

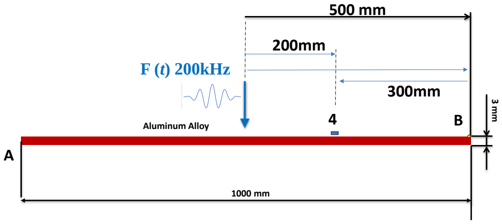


Figure 1. Plate model for the time domain explicit transient analysis

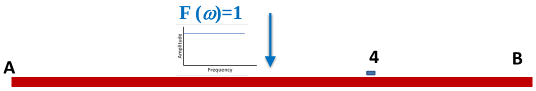


Figure 2. Plate model for the frequency response analysis

While the time domain analysis (explicit transient) must be repeated to generate a guided wave at a different frequency or use a different waveform (for example, when the damage size is unknown and the wavelength must be tuned accordingly), the frequency analysis allows to reconstruct the time response for any waveform and frequency, according to the frequency range in which the frequency response function has been calculated. For a generic waveform and frequency of the input force, the time domain wave propagation is reconstructed from the frequency response analysis multiplying the frequency response function by the forcing waveform transformed into the frequency domain (the discrete fast Fourier transform of the source), and the resulting function is then back transformed into the time domain by performing and inverse fast Fourier transform. Figure 3 schematically shows the time domain reconstruction.

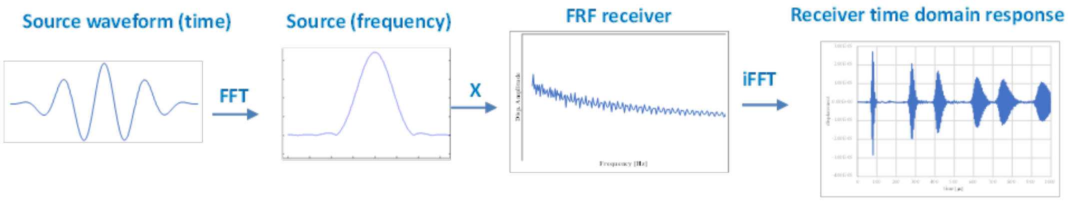


Figure 3. Reconstruction of the time domain response from the frequency response

The advantage of this approach is that once the frequency response function analysis has been carried out in the desired frequency range, a very quick data postprocessing allows to obtain the time domain wave propagation reconstructed. Moreover, this post process may also be skipped in many circumstances if a damage detection is desired: if a damage occurs, the variation of both the amplitude and the phase of the frequency response functions carries important information about the damage location and extension. This point will be showed in the next paragraph concerning the layered plate with a delamination.

GUIDED WAVES IN A LAYERED PLATE

Transient time domain and frequency response analyses have been carried out on the plate showed in Figures 1 and 2. Figure 4 shows the guided waves propagating and recorded by the receiver 4 (200 mm away from the source) when the source generates 4.5 sine cycles Hanning windowed and a central frequency of 200 kHz as calculated with an explicit transient solver. Figure 5 shows the reconstruction of the TD response from the FRF at the same location for the same excitation (4.5 sine cycles Hanning windowed at 200 kHz), according to the above described procedure. By comparing the curves in figures 4 and 5 we can state that the frequency analysis allows to reconstruct both the incident So and Ao modes and the reflections coming from the edges A and B of the plate, and the waveforms are in perfect agreement. Similar considerations can be done on the subsequent reflections coming to the receiver 4, taking in mind that for the analysis time of 1000 μs the waves generated travel about 3 m and are reflected from each boundary (point A and B of Figures 1 and 2) at least two times.

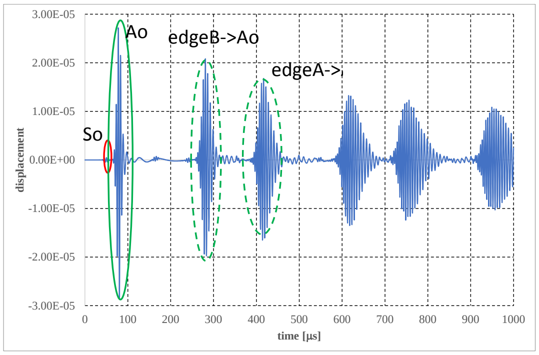


Figure 4. Numerical solution from transient explicit analysis: edgeB->Ao and edgeA->Ao are the reflections of the Ao mode coming from the plate edges A and B, respectively

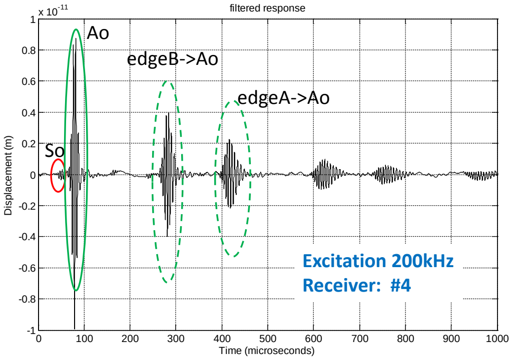


Figure 5. Numerical solution reconstructed from frequency response analysis

Moreover, using the calculated frequency response data, the analysis at every different frequency becomes much faster than transient analysis: Figure 6 shows the signal received at the location #4 for an input signal with a central frequency of 400 kHz. It is interesting to note that at this frequency the amplitude of the So mode is greater than in the previous case, as predicted by theory. No other modes than So and Ao are present since the maximum frequency-thickness is below the cut-off one (about 1.5 Mhz x mm).

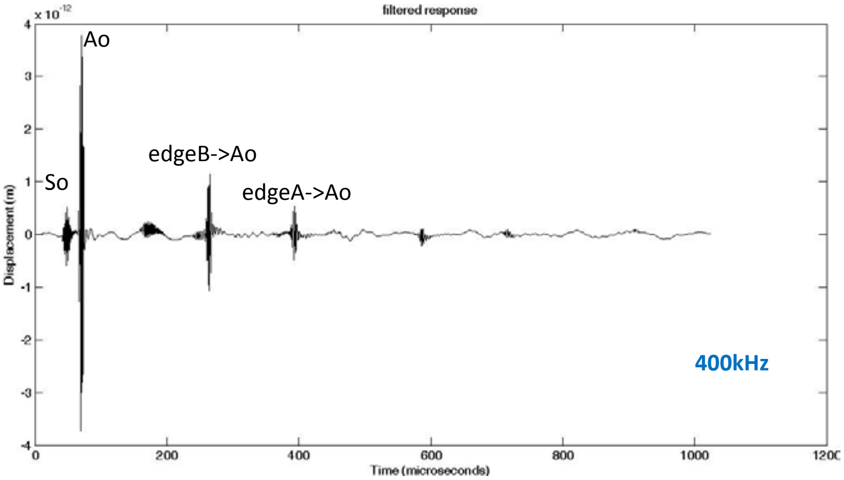


Figure 6. Numerical solution reconstructed from frequency response analysis for an input source with a central frequency of 400 kHz

LAYERED PLATE WITH A DELAMINATION

The comparison of the time and frequency domain approaches has been applied to the same plate with a 18mm long delamination located between the source and the receiver 2, as showed in the Figure 7

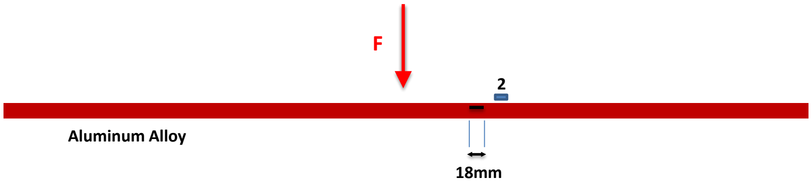


Figure 7. Numerical model of the delaminated plate

Figures 8 and 9 show how the time domain data can be well reconstructed from the frequency response ones.

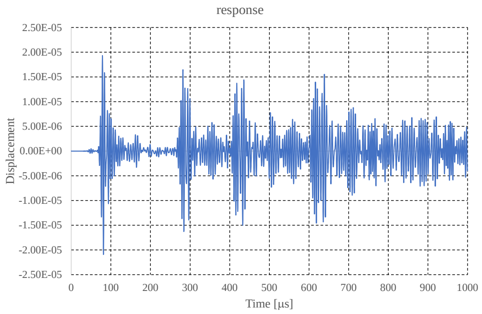


Figure 8. Numerical solution of the damaged plate (transient explicit analysis)

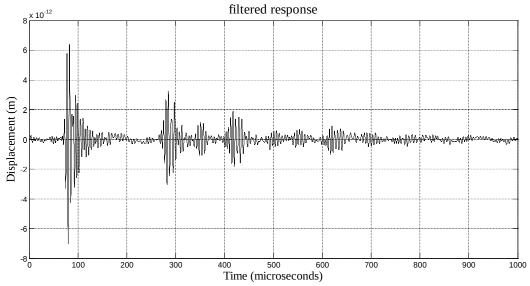
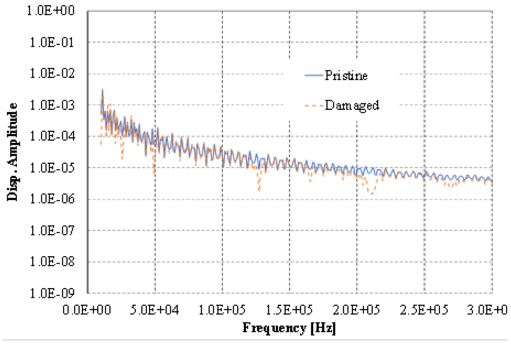


Figure 9. Numerical solution of the damaged plate reconstructed from frequency response analysis

Moreover, the onset of delamination can also be assessed by frequency analysis. In Figures 10 and 11 the frequency response at the receiver 2 are showed, as amplitude and phase. A significant phase shift is observed starting from a frequency of about 100 kHz, at which frequency the wavelength of the antisymmetric mode is about 25 mm and approaches the size of the defect (18mm). The phase shift becomes larger as the frequency increases (the wavelength decreases): the elastic wave interacts more with the damage.



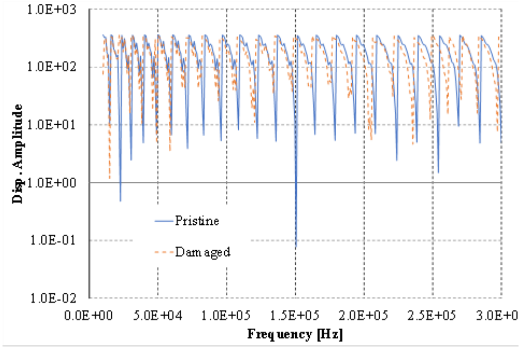


Figure 10. Pristine and damaged plate: FRF amplitudes

Figure 11. Pristine and damaged plate: FRF phases

THE HOLLOW CYLINDER

A hollow cylinder with a diameter of 300 mm, a wall thickness of 2 mm and made of aluminum alloy (Young modulus 70 GPa) was considered as further test case. In thin-walled curved shells with a thickness to radius ratio less than 1/10, guided waves propagate circumferentially with helical path and are called helical guided ultrasonic waves (HGUW). Considering a pair of points, they travel with multiple trajectories, and each of them is indexed as the order of the HUGW trajectory. When they intercept a defect, their interaction with it allows to determine its presence [1].

Also, for this test case both the transient time and the frequency response analyses were performed, and from the latter the time response reconstructed. Figure 12 shows the test article with the source and receiver positions and the helicoidal path.

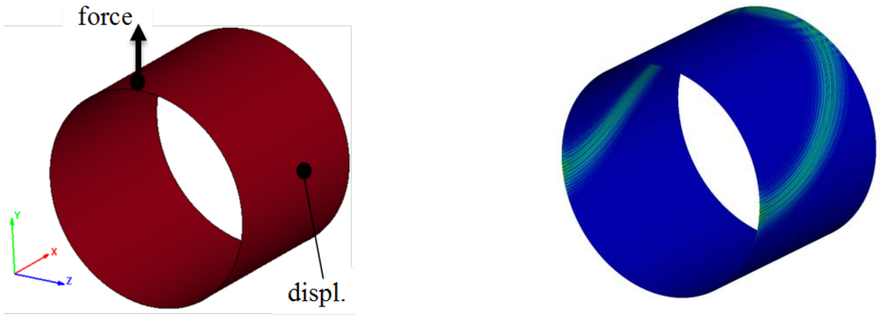


Figure 12. The hollow cylinder

A 200 kHz point load (4.5 sine cycles in Hanning window) is applied on one end of the cylinder in the XY plane along the Y axis and the response is calculated on a receiver positioned at a distance of 100 mm from the source on the cylinder surface in the XZ plane and along the Z-direction (i.e. at 90° respect to the surface load). Figures 13 and 14 show the results of the two approaches: an excellent agreement is achieved using the two methodologies described in the previous paragraph (time domain and time domain reconstructed from the FRFs).

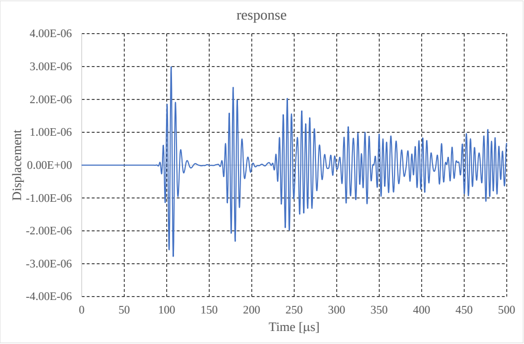


Figure 13. Numerical solution of the hollow cylinder (transient explicit analysis)

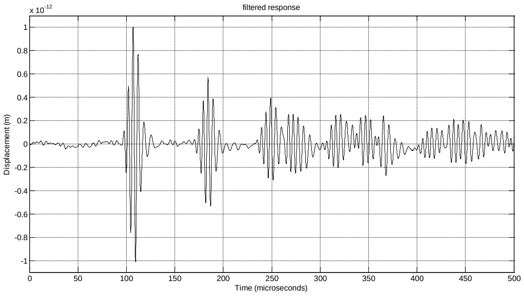


Figure 14. Numerical solution of the hollow cylinder reconstructed from frequency response analysis

CONCLUSIONS

In this paper it has been demonstrated how that frequency response functions allow both to reconstruct the wave propagation in the time domain in a very efficient way and to directly give information on the occurrence of a damage and estimate its size. The time domain analysis of GW propagation can be efficiently reconstructed from the frequency response functions for any input load (waveform and frequency). Although not highlighted in this work for the sake of brevity, the frequency analysis requires some attention to the frequency resolution adopted to obtain the FRFs and often the adoption of appropriate filters before transforming the data into the time domain. Depending on the accuracy of the results that one wants to obtain and taking into account the computational efficiency, the calculation of the FRF can be done either with the direct or modal method.

SYMBOLS

GW	Guides Waves
DFRA	Direct Frequency Response Analysis
MFRA	Modal Frequency Response Analysis
FD(A)	Time Domain (Analysis)
TD(A)	Frequency Domain (Analysis)
FRF	Frequency Response Function

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