COMPUTATIONAL MODELING AND VALIDATION OF GUIDED WAVE DISPERSION CURVES IN A PIPELINE USING ANSYS

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Abstract: In this paper, the numerical modal analysis is proposed to estimate the dispersion curves for a specific waveguide. In general, FEM-based procedures provides an efficient solution to determine the dispersion curves of an arbitrary waveguide cross-sectional. The dynamical analysis is performed in the commercial package ANSYS and the postprocessing stage of the data is executed in Matlab. Modal analysis yields hierarchically eigenvalues (resonant frequencies) with its respectively eigenvectors (mode shapes) in a range of frequencies. Thus, for a specific length of specimen, it is possible to establish a relationship between the sequentially order of eigenfrequencies and the order of its modes to estimate wavelength for each resonant frequency. So, the couple frequency with wavelength are the foundation for generate the rest of dispersion curves, i.e. wavenumber versus frequency, phase velocity versus wavenumber and finally, group velocity versus frequency. In this work, the dispersion curves for an isotropic hollow cylinder are obtained based on its dynamic analysis and the obtained curves are compared with the results of the software GUIGW. Numerical results are in good agreement with the results offering by the specialized tool GUIGW.

Keywords: Guide waves, ANSYS (APDL), Dispersion curves, Modal analysis.

1. INTRODUCTION

In industry, integrity assessment of long-distance pipelines faces demanding challenges. It is claimed a new technology capable of determining mechanical damage such as dents, cracks, and surface issues in an economical, practical, and reliable way. The guided wave technique is emerging as a suitable candidate to evaluate the structural health in this type of facility. Guided waves technique is a ultrasonic-based non-destructive testing (NTD) used in structural inspections tasks which recently has been gained the attention of the community of the structural health monitoring. This technique is preferred to conventional ultrasonic analysis, due to although the launched spot covers a small area, the ultrasonic radiated permits scan big volumes of the specimen. The low-frequency ultrasonic pulse travels along the waveguide achieving the detection of discontinuities at great distances from the point of emission, including places of difficult or no access, thus avoiding the removal of protective bodies of the structure and performing the inspection at high speeds.

The complexity of the propagation of the guided waves is in the vast number of propagation modes and its different phase velocities, and how the ultrasonic energy is distributed in the cross-section. Now, the knowledge of the phase velocity is the capstone of the propagation of the wave because this feature is the base of the failure location or the discontinuity in the pipe. The relevant study of the propagation of a guided wave in a specific structure leads to the obtention of dispersion curves; in them, detailed information about the waveforms that are exhibited in such structure can be appreciated. For example, it is possible to observe which modes tend to be very dispersive, which affects the propagation of the wave, shortening its path through the medium and making it difficult to determine times of fly (TOF) essentials to locate discontinuities. On the other hand, when the inspection faces with irregular geometric bodies, obtaining the dispersion curves in an analytical way is a complex task, and may even be unsolvable. Technical problems such as geometric attenuation and wave reflections make it difficult to propagate the wave, causing wavefronts to be redistributed throughout the medium, allowing large amounts of energy to be dispersed. For simple geometric bodies such as plates or pipes, it is an already extremely complicated process. For this reason, computational tools based on numerical methods are used, specifically the Finite Element Method (FEM), which guarantee and facilitate to a great extent the development of this research proposal.

For years, different studies on wave propagation in isotropic and elastic structures were carried out, to describe the static and dynamic behavior of the waves in solids. The main purpose is to propagate the elastic waves under some specific directions with low attenuation to reach long-distance of inspection. One important aspect to generate guided waves is that the volumetric body must present a much smaller dimension than the other dimensions, causing it to become a waveguide. The approximate theory of plates allows to approach the problem and similarly facilitates the analysis, reducing quantitatively the equations and the computational effort which represents a considerable advantage with respect to other possible schemes in the obtaining of vibration modes and their respective dispersion curves.

The waveform of a guided wave is the result of the superimposition of different waveforms that propagate in different directions and are independent of each other, interacting with the surroundings, reflecting and refracting with any obstacle in the structure, including its boundaries. The modal forms present in an isotropic material elastic structure that meets the above conditions admit two infinite sets of modes, whose velocities depend on the relationship between the wavelength and the thickness of the plate. These modes are found in the low-frequency range and are commonly referred to as the longitudinal mode and the torsional mode which describe the nature of the motion. The importance of these two types of modes lies mainly in the amount of the transported energy, which is greater than the present in the higher order modes. In addition, to achieve the simulation of an external disturbance that generates harmonic elastic waves, a coupling is made in the transversal faces of the structure.

This article explains the procedure for obtaining the dispersion curves of a commercial Schedule 40 elastic, isotropic and finite pipe, using the commercial FEM program ANSYS (APDL) in its version 18.1, by means of its "Modal Analysis" library, where the natural frequencies and their mode shapes will be determined. Then, the data is exported to the numerical calculation program MATLAB R2018b for post-processing of the data and eventually obtaining the dispersion curves.

2. METHODOLOGY

In a hollow pipe of standard dimensions, the modal analysis yields three types of vibration modes: Torsional, Longitudinal, and Flexural. In order to develop a model of low computational cost, it is proposed a dimensional reduction of the model, projecting the pipe cross-section and performing its modal analysis using the Finite Element Method [1], and to process it with the ANSYS program (Mechanical APDL 18.1).

As shown in Figure 1, the cross-section plane is a rectangle with the original dimensions of the pipe, in this way, using the Approximate Plate Theory [2] the model can be considered as an isotropic plate with its material properties such as Young's modulus and Poisson's ratio [3], to guarantee the acquisition of the longitudinal and flexural modes, which have displacements in axial and radial direction, respectively.

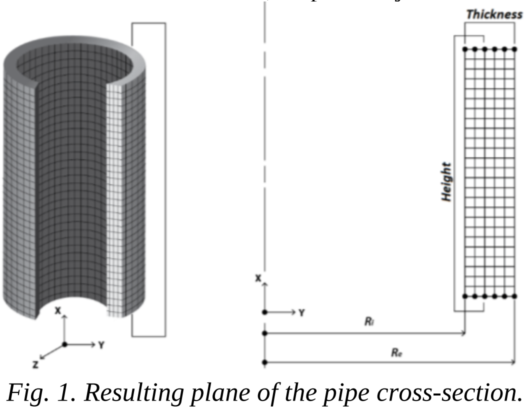

Fig. 1. Resulting plane of the pipe cross-section.

In addition, it is required to estimate the torsional modes, which presents displacement in the direction of the circular section of the pipe, specifically in the Z direction with respect to the specified Cartesian plane specified in the setup. In order to assure the obtention of the torsional waves, it is necessary to allow the structural section of the model, specifically the nodes that form it, to move in the three dimensions (X, Y, Z), which is possible selecting for the elements the PLANE25 type from the ANSYS standard library, which is composed of four nodes with three degrees of freedom (DOF) . Figure 2 shows this element:

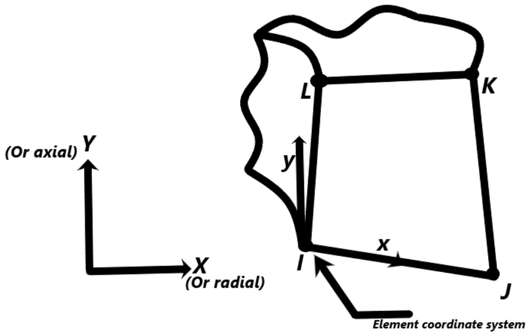

Fig. 2. Description of the PLANE element 25.

Next, the cross-section is dimensioned, and the material properties are defined. Finally, the boundary conditions at the upper and lower ends of the model are configurated. This condition is based on the coupling between the exactly opposite nodes implemented using the "coupling /Ceqn" command. During the coupling, a reasonable tolerance must be guaranteed between coupled nodes.

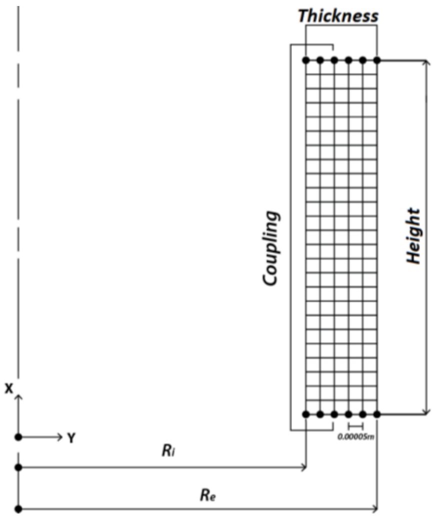

Fig. 3. Schematic representation of the node coupling.

With respect to the modal analysis, the range of frequencies to excite the structure and the number of modes is defined. Although, ANSYS allows specified the number of frequencies, this number is determined by the length of the pipe, as a result of the relationship between the wavelength and the length of the specimen through this analytical relation : $\lambda = L/P$, where P can take integer values of P=1,2,3...

As mentioned above, for a tubular structure three types of families of modes may emerge: Torsional, Longitudinal and Flexural. The different modes can be classified by a visual inspection via ANSYS graphic viewer which also provide the means for calculating the wave number (λ) with respect to the frequency under study. However, this option is inefficient for a large number of frequencies. Therefore, the mode selection process is automated using the modal shape.

Each modal shape, eigenvector, is expressed in different nodal displacements. So, a code based on conditionals and logical cycles is used in conjunction with the implementation of the MAC number (Modal Assurance Criterion) to compare the different modal shapes may classify the frequencies in their respective modes. Substantial difference between the different modes are expressed for the low correlation between the nodal displacement for the different families of modes and among different modes of the same family.

As a result of the modal analysis, ANSYS only lists the resonance frequencies and its modal shapes (eigenvalues and eigenvectors). The process for propagation modes classification begins with a randomically selection of a set of nodes in the cross-section or in the Y-direction, as shown in Figure 4. The shape displayed by the displacement vector of this set of nodes will be utilized for categorizing the type of mode (mode shape) with respect to their respective frequency.

Due to the coupling between the nodes in the upper and lower sections (boundary conditions) the pre-selected set of nodes will present homologous displacements. This nodal displacement of the total valid frequencies obtained from the modal analysis is used to assembly a big matrix. Based on the only z-direction nodal displacements for Torsional modes a simple procedure is implemented to classify this family of propagation modes. The rest of eigenvectors belongs to either longitudinal or flexural modes. To discriminate between this propagation modes families and among the propagation modes of the same family MAC is used (which conditions the comparison to two vectors that correspond to the modal forms) [4]. In the case of modes family classification (flexural and longitudinal modes), a threshold of 0.9 in number MAC is used as a criterion for establishing similarity between two modal shapes. After the first comparison, the process continues by preserving the modal shape of the first frequency of comparison fixed and alternating the other modal shapes for the other frequencies as the cycle progresses, until all eigenvectors with its respective frequencies within the matrix are compared. As a result, the Torsional, Flexural and Longitudinal modes are obtained in independent vectors with their respective frequencies. Due to the symmetry condition that emerge by the coupling repeated values of resonance frequencies are presented, so they are eliminated. Then, with the coordinates (λ, ω)calculated, follows the determination of the other coordinates of the dispersion curves.

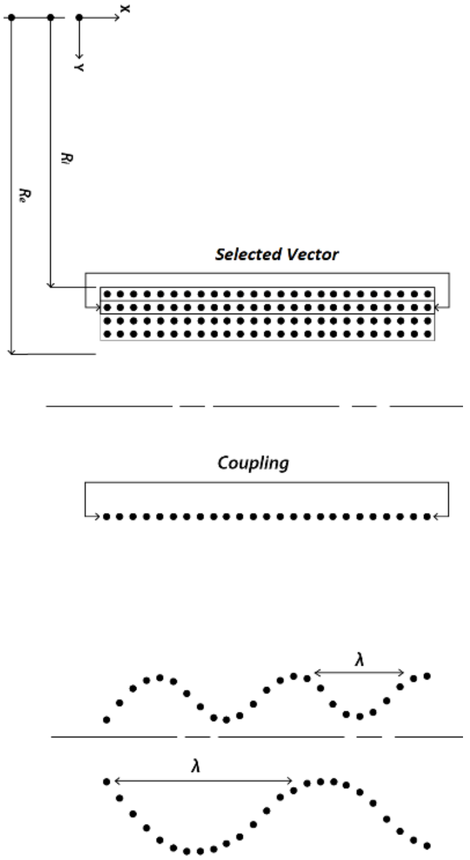

Fig. 4. Node Displacements for different propagation modes.

As the group velocity C_g is defined by $C_g = d\omega / d\xi$, where ω is the radial frequency and ξ is the wave number, it is necessary to implement a numerical method to obtain that derivative. In this work it was used the Finite Difference Theory [3], [5] for which it is required to obtain the nodal displacements of the structure with a deviation in its Y-direction (length of the pipe), for studied case is assumed a variation of 2.5% of its original length. Finally, using the equations described in [5].

3. RESULTS

In Figures (5-8) are presented the dispersion curves for a pipe of 4" NPS, sch 40, density of 7800 kg/m3 and Poisson of 0.33. In these figures, the curves generated by GUIGUW software are superimposed on the curves obtained this approach.

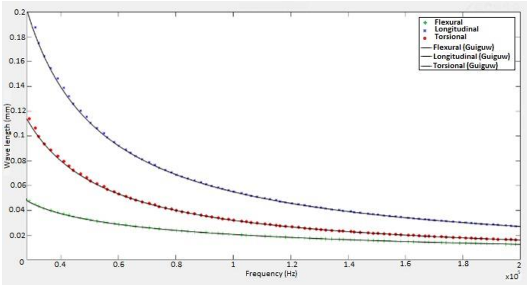

Fig. 5. Wavelength vs Frequency.

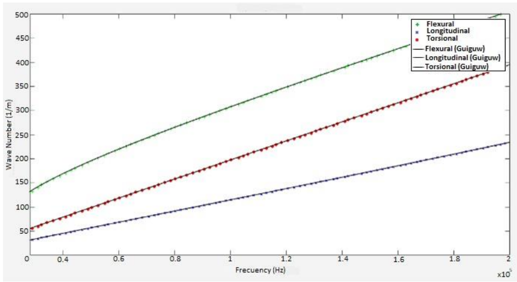

Fig. 6. Wave number vs. frequency.

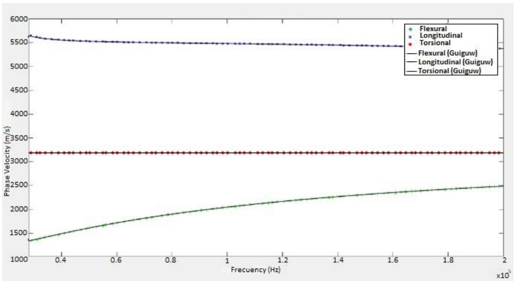

Fig. 7. Phase Velocity vs Frequency

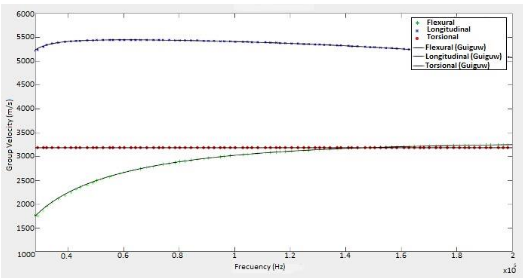

Fig. 8. Group velocity vs. frequency

As for the dispersion curves, each representative value comes from the frequencies obtained in ANSYS. The estimated frequencies are conditioned to the length of the modeled specimen. Thus, to obtain a wide range of values, a greater number of wavelengths must be guaranteed, which is possible by increasing the height of the cross-section.

5. CONCLUSIONS

In this work, the dispersion curves of a commercial steel pipe are obtained using a modal analysis in ANSYS. The studied approach allows initially the calculation of the respective resonance frequencies and vibration modes of cylindrical specimens in ANSYS. The dynamic analysis is based on a simplification of the specimen geometry via a 2D model reducing the computational cost at this stage of the calculation. Eigenvalues and eigenvectors are used in the postprocessing stage in Matlab to generate the dispersion curves. Finally, comparing the results of this approach with the curves generated by the software GUIGW, it can be noted a good agreement in all the estimated curves with a reasonable computational cost.

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