Predicted and Measured of the Group Velocity of Circumferential Waves Propagating Around the Tube using the ANFIS and Time-frequency Techniques

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In this study, the analysis and the characterization of the acoustic circumferential wave dispersion are studied through the group velocity of these waves. The time-frequency representation of Wigner-Ville and the ANFIS approaches are used to predict and to measure the group and the phase velocities of symmetric S0 and the anti-symmetric A1 circumferential waves propagating around the steel tube immersed in water with radii radio b/a (a: outer radius and b: inner radius). The proper modes theory of these acoustic waves is used in this paper to compare the velocity values determined through the Wigner-Ville time-frequency representation and the ANFIS approaches. These techniques are able to determine the velocities of symmetric and the anti-symmetric circumferential waves with a high precision of the different errors. A good agreement is obtained between the output values predicted using the propose approaches and those computed by the proper modes theory of symmetric S0 and the anti-symmetric A1 circumferential waves.

1 Introduction

In previous studies [1-11], we have studied and analysed the dispersion of the acoustic circumferential wave propagating around the tube, to extract the information such as cutoff frequency, longitudinal and transverse velocities. In the previous work [1,6], we have shown that it is possible to accurately determine, on a concrete example, the group velocity of the acoustic waves from a time-frequency representation of a signal backscattered by a tube immersed in water. In other previous work [2-3], we have also shown that there is a similitude between the cutoff frequencies of the Lamb waves in the case of a thin plate having a thickness e and the cutoff frequencies of waves circumferential propagating around a tube of radius ratio b/a >= 0.9 with e = a-b. This similitude shows that, from a time-frequency representation we can extract different cutoff frequencies of acoustic waves A1, S1, S2, A2. These different studies are based on the time-frequency representation of Wigner-Ville and the application of the fuzzy logic approach. From the results already obtained in this research, we were able to extract other acoustic parameters via the two approaches mentioned previously [1-11] and the present paper is specially concerned with the combination three approaches such as time-frequency, fuzzy logic and proper modes theory. The acoustic parameters selected in this study are the group and the phase velocities of symmetric S0 and the anti-symmetric A1 circumferential waves propagating around the steel tube immersed in water with radii radio *b/a*.

2 Dispersion characterization

2.1 Impulse responses of tube

The scattering of an infinite plane wave by a tube of radii ratio equal to *b/a* (outer radius *a* and inner radius *b*) is investigated through the solution of the wave equation and the associated boundary conditions. The figure 1 shows the geometry used for formulating the sound backscattering from an elastic tube. There is a plane sound wave of circular frequency ω incident along the *x* axis. The fluid 2 inside the shell has a density of ρ' and a propagation velocity c'. In general, the outer fluid 1 will be different and is described by parameters ρ and c. Let a plane wave incident on an infinite tube with air-filled cavity (fluid 2), be submerged in water (fluid 1). The backscattered complex pressure P_{diff} by a tube in a faraway field ($d >> a$, we have neglected the diffraction of waves and one receives only the part backscattered of the complex pressure field) is the summation of the incident wave, the reflective wave ①, surface waves tell shell waves ② (whispering Gallery, Rayleigh, ...) and Scholte waves (A) ③ connected to the geometry of the object (figure 1). The waves ② and ③ are the circumferential waves. For these waves one distinguishes the waves A, the symmetric waves S0, S1, S2 and the anti-symmetric waves A1, A2 [8]. In our case, the waves *S0 and A1* can be observed on this complex spectrum.

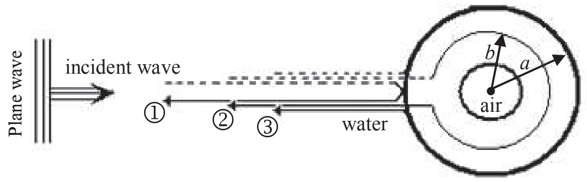

Figure 1: Mechanisms of the echoes (specular reflection ① and circumferential waves (② and ③) [11])

The figure 2 illustrates the backscattered spectrum as a function of the reduced frequency ka (without unit) given by:

$$ka = \frac{4\pi}{c(1-\frac{b}{a})} f \frac{e}{2} \quad (1)$$

Where f is the frequency of a wave in Hz and e is the plate thickness (e=a-b).

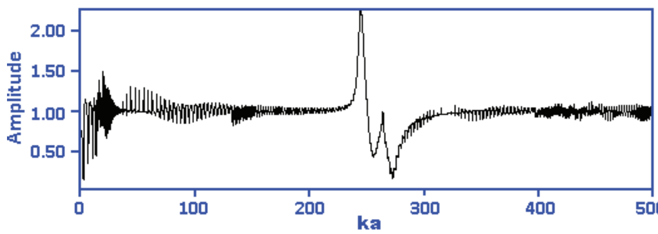

Figure 2: Backscattered spectrum for a steel tube with air-filled cavity, *b/a*=0.95

This spectrum is computed for a steel tube [8]. The succession of echoes in this spectrum is connected with the propagation of circumferential waves. The temporal signal backscattered from a tube is obtained by the Inverse Transform Fourier of the backscattered spectrum [8]. The figure 3 presents this signal and shows the specular reflection ① one can observe several wave packets ② and ③ associated with different circumferential waves. The observation of the temporal signal (figure 3) shows a succession of components more or less distinct that one seeks then to identify. The different echoes finish by overlapping and in these conditions, the identifications and measures of arrival times of echoes become difficult, perhaps impossible. This constitutes a major disadvantage of the temporal approach. In the following, a large attention will be given to the analysis of the Wigner-Ville time-frequency representation for the dispersion of circumferential waves.

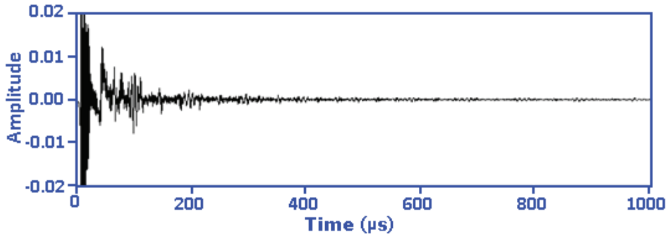

Figure 3: Impulse response of a steel tube with air-filled cavity, *b/a*=0.95

2.2 Methodology used

Figure 4 shows the methodology used in this study and the comparison between the time-frequency and ANFIS approaches. This methodology is based on two approaches:

First one: Extract the backscattered by the tube, then applied the technique time-frequency to the signal. The group velocity is determined from the time-frequency mage obtained. From these velocity values, we determined the phase velocity values.

Second one: Extract the backscattered by the tube and applied the ANFIS and the modes theory proper techniques predicate and determine the phase velocity values. The group velocities are determined from the velocities predicted by ANFIS approach.

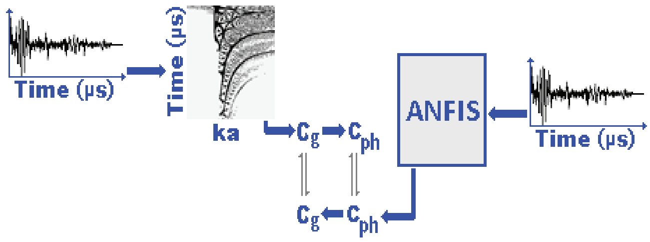

Figure 4: The methodology used and the comparison between the two approaches

2.3 Time-frequency approach

In this study, one is interested only in the circumferential waves S0 and A1. According to this spectrum (figure 2), the reduced frequencies scale in which appears the symmetric wave S0 is 50<*ka*<125, and *ka*>130 for the anti-symmetric wave A1. Figures 5 and 6 show the time-frequency images for steel tube. On each of these images, we have noticed that the proper terms of the signal (circumferential waves S0 and A1) are well localised. The different time-frequency images show synthetic images, from which can follow the evolution of the frequentiel content of the circumferential waves S0 and A1 in time. For the time-frequency image (figure 6), the low frequencies part of the circumferential wave A1 arrives more belatedly than high frequencies part. This means that the group velocity of this wave increases in function of frequency. When the time augments, the trajectory associated to wave A1 (figure 6) tends to an asymptotic value which equals the reduced cutoff frequency $(ka)_c$ of this wave.

In this work, from the Wigner-Ville images (figures 5 and 6) we have estimated the time of group delay (equation 14 [8]). The group velocity is determined from the equation 15 [8], in function of frequency. This allowed us to draw the curves for the dispersion of low circumferential waves. On comparing the results obtained with time-frequency images and those obtained with the method of proper modes theory (equation 5 [8]).

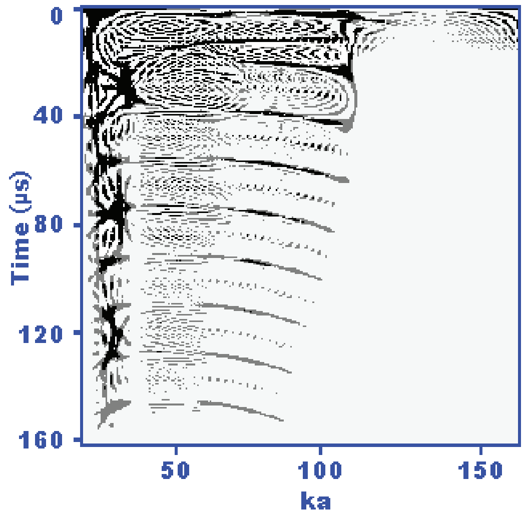

Figure 5: Time-frequency image for S0 wave

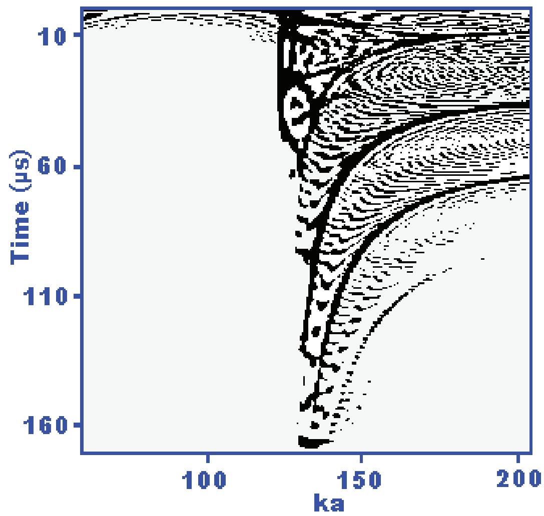

Figure 6: Time-frequency image for A1 wave

2.4 Velocity group dispersion of waves

One of the most important points is to find out some parameters that carry most of the information available from the response of the shell. Such parameters may be found from the velocity dispersion of the circumferential waves, since it is directly related to the geometry and to the physical properties of the target. The phase velocity c_{ph} is estimated from the resonance frequencies that correspond to circumferential waves adding in phase along the surface of the shell. Thus, for each resonance frequency ω, an integer number of wavelengths fits the circumference of the cylindrical shell, and the following relation holds [1]:

$$c_{ph}(\omega) = \frac{\omega a}{n} \qquad (2)$$

where n is the circumferential wave mode.

The estimation of the phase velocity dispersion that corresponding to the detection of resonance frequencies given by the zeros of $D_n(\omega)$ in equation (1) [1]. In addition, group velocity dispersion c_g is deduced from the phase velocity c_{ph} using the relation [1]:

$$c_g(\omega) = c_{ph}(\omega) + \omega \frac{\partial c_{ph}(\omega)}{\partial \omega} \qquad (3)$$

Figure 7 shows the phase velocity dispersion in function of the reduced frequency ka of two different circumferential waves in the case of the tube. Figure 7 presents a first curve, noted S0, that corresponds to the symmetric circumferential wave. When the reduced frequency increases, the curve of wave S0 presents a first palliate with a 5850 m/s velocity. One should remark that if the shell is thin, then the palliate of the curve S0 is long. The second curve, noted A1, presented in the same figure corresponds to the anti-symmetric circumferential wave. For a high frequency, the symmetric circumferential wave S0 tends to the Rayleigh velocity, and the anti-symmetric circumferential wave A1 tends to the transversal velocity of the tube c_T=3140 m/s. The phase and group velocity are functions of the reduced frequency ka. When these velocities depend on the reduced frequency, the propagation is termed dispersive. For the symmetric circumferential wave S0, the associated dispersion curve is almost non dispersive like in the case of Lamb wave propagation on plates, except in the low frequency range where velocity dispersion is significant. Of considerably greater interest is the velocity dispersion of the anti-symmetric circumferential wave A1. The anti-symmetric circumferential wave A1 is identical to the anti-symmetric Lamb wave propagated in the plate [1-2,8].

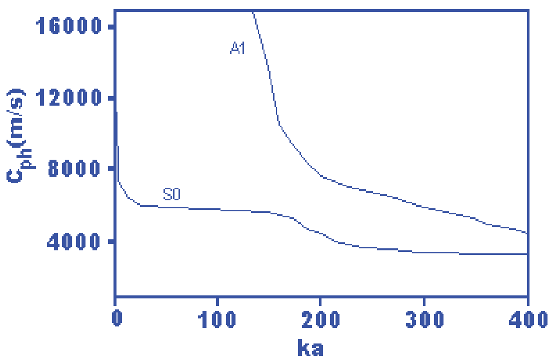

Figure 7: Phase velocity dispersion for a steel tube with empty cavity (c_L=5880 m/s, c_T=3140 m/s, ρ=7800 kg/m^3, b/a=0.95)

Figure 8 shows the group velocity dispersion of the two circumferential waves S0 and A1 given by the relation (3). For a low frequency, the anti-symmetric circumferential wave A1 has a cutoff frequency $(ka)_c$=134. This cutoff frequency is obtained by the relation:

$$(ka)_c = \frac{\pi c_T}{c(1 - \frac{b}{a})} \qquad (4)$$

where c_T is the transversal velocity of the cylindrical shell.

This circumferential wave A1 will not propagate if the reduced frequency ka is lower that the cutoff frequency 134.

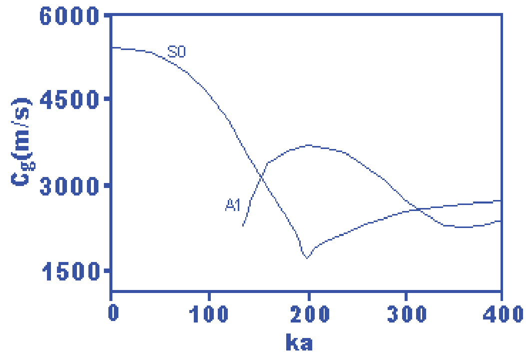

Figure 8: Group velocity dispersion for a steel tube with empty cavity (c_L=5880 m/s, c_T=3140 m/s, ρ=7800 kg/m^3, b/a=0.95)

2.5 Fuzzy logic approach

The fuzzy logic technique used is the Adaptive Neuro-Fuzzy Inference System (ANFIS). In this paragraph, we have used the ANFIS architecture detailed in the previous studies [4-5,7,9-10]. The data base of Fuzzy logic approach is collected to involve and test the performance of the model starting from the results obtained by the time-frequency technique and the proper mode theory of the circumferential waves. The density of material, the radius ratio, the transverse and longitudinal velocities, the index of the anti-symmetric and symmetric circumferential waves are retained like relevant entries of the model because these parameters characterize the tube and the types of circumferential waves propagating around this one. The phase velocity of the anti-symmetric and symmetric circumferential waves (S1 and A1) for a steel tube constitutes the output of fuzzy logic approach.

3 Resultants and discussion

The figures 9 and 10 show the training data and validation performances of ANFIS approach. These results are determined for each ANFIS architecture based on the number of rules and the error values.

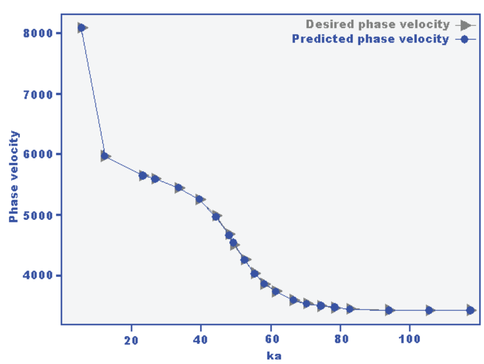

Figure 9: Training data set of phase velocity of symmetric circumferential wave S0

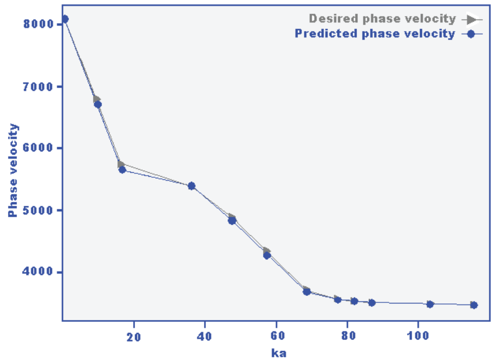

Figure 10: Validation data set of phase velocity of symmetric circumferential wave S0

The error values are illustrated in the tables 1 and 2.

Table 1: Error values for the symmetric circumferential wave S0

Nombre of rules	4
MRE	0.001
R	0.98

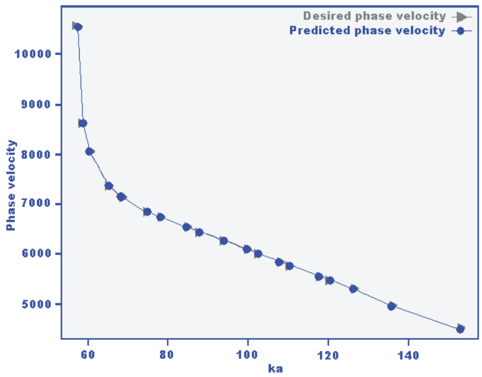

Figure 11: Training data set of phase velocity of anti-symmetric circumferential wave A1

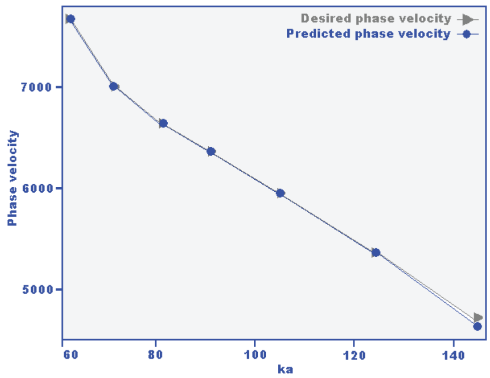

Figure 12: Validation data set of phase velocity of anti-symmetric circumferential wave A1

Table 2: Error values for the anti-symmetric circumferential wave A1

Nombre of rules	4
MRE	0.002
R	0.98

The velocity values obtained are considered as very satisfactory.

4 Conclusion

The time-frequency of Wigner-Ville and ANFIS approaches applied in this study are used like new non-destructive measurement techniques to characterize the dispersion of group and phase velocities of the anti-symmetric and symmetric circumferential waves. These approaches permit to predict and to measure the phase and group velocities of the anti-symmetric A1 and symmetric S0 circumferential waves propagating around the tube. This paper uses a new tool for dispersion of circumferential acoustic waves. These approaches allow to predict and to determine automatically and with good precision the values of the velocities of circumferential waves. The R^2 value is close to the value 1.

5 References

[1] R. Latif, E. Aassif, G. Maze, A. Moudden, B. Faiz, “Determination of the group and phase velocities from time-frequency representation of Wigner-Ville", Journal of Non Destructive Testing & Evaluation International, Vol.32, 7, pp. 415-422, (1999)

[2] R. Latif, E. Aassif, A. Moudden, D. Decultot, B. Faiz, and G. Maze, “Determination of the cut-off frequency of an acoustic circumferential wave using a time-frequency analysis,” J. NDT&E Int., vol. 33, pp. 373–376, (2000)

[3] R. Latif, M. Laaboubi, E. Aassif, A. Moudden, G. Maze, “Determination of the cut-off frequency of the anti-symmetric circumferential waves using the time-varying autoregressive TVAR“, 3rd International Symposium on Communications, Control and Signal Processig IEEE ISCCSP’08, pp. 357-361, St Julians Malta, 12-14 March (2008)

[4] Latif R., Nahraoui Y., Aassif E., Maze G., “Measured and predicted of the longitudinal and transverse velocities of tube material using the Wigner-Ville and fuzzy logic techniques”, Acoustics’12 Nantes, France, 23-27 April (2012)

[5] Y. Nahraoui, E. Aassif, G. Maze, R. Latif, "Modeling the Cut-off Frequency of Acoustic Signal with an Adaptative Neuro-Fuzzy Inference System (ANFIS)", International Journal of Advanced Computer Science and Applications, Vol. 4, n° 6, pp. 23 - 33, (2013)

[6] R. Latif, E. Aassif, M. Laaboubi, G. Maze, "Determination of group velocity using the time-varying Autoregressive TVAR", Conference international IEEE ISSPA, Sharjah UAE (2007)

[7] Y. Nahraoui, E. Aassif, R. Latif, G. Maze, "A neuro-fuzzy computing technique for modeling the acoustic", The 3rd International Conference on Information Systems and Technologies, Tangier, Morocco, March 22 – 24, (2013)

[8] R. Latif, E. Aassif, G. Maze, D. Decultot, A. Moudden, B. Faiz, "Analysis of the circumferential acoustic waves backscattered by a tube using the time-frequency representation of Wigner-Ville", Journal of Measurement Science and Technology, Vol. 11, 1, pp. 83-88, (2000)

[9] Y. Nahraoui, E. Aassif, R. Latif, G. Maze, "Modeling the cut-off frequency of acoustic signal with a fuzzy

logic system", International Conference on NETworked sYStems, Marrakech, Morocco, May 2-4 (2013)

[10] A. Dariouchy, E. Aassif, G. Maze, R. Latif, D. Decultot, M. Laaboubi, "Prediction of the Acoustic Pressure Backscattered by a Steel Tube Using Neural Networks Approach", International Symposium on Computational Intelligence and Intelligent Informatics ISCIII'07, Agadir Morocco, 28-30 March (2007)

[11] R. Latif, E. Aassif, M. Laaboubi, G. Maze, "Détermination de l'épaisseur d'un tube élastique à partir de l'analyse temps-fréquence de Wigner-Ville", Acta Acustica united with Acustica, Vol. 95, pp. 253-257, (2009)