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Acoustic Scattering from Bi-Layered Cylindrical Shells: Influence of the Layers Thicknesses on the Guided Waves

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Summary
The current work focuses on the study of acoustic scattering from bi-layered stainless steel-copper and copper-stainless steel cylindrical shells filled with air and immersed in water. This paper is interested in revealing the effects of physical and geometrical characteristics of the layers constituting the shells on the scattering phenomenon. The object of this work, is to study the influence of the layers thicknesses on guided waves, the overall thickness of the shells is fixed. The plane of modal identification was chosen to analyze the scattering phenomenon. We investigate the resonance trajectories of the guided waves, especially the curves change. The investigation and comparison made on resonance trajectories, show a shape change, a gradual deviation, or both, appear on the resonance trajectories of different guided waves, for the reduced cutoff frequencies of guided waves a sliding to higher and lower value are noticed. The interaction between guided waves is also manifested in the scattering phenomenon. The findings for the bi-layered cylindrical shells are then compared with those obtained for the mono-layered stainless steel and copper cylindrical shells. Then, this work is completed by an investigation on the reduced cut-off frequencies of the A_1 wave, that have been extracted for different possible values of the intermediary radius. In this part, to understand the observed phenomena, other examples of bi-layered cylindrical shells are introduced. The obtained results are analyzed and investigated.

PACS no. 43.20.Fn, 43.20.Mv

1. Introduction

If an air-filled elastic cylindrical shell immersed in water, excited by a plane acoustic wave perpendicularly to its axis, two types of circumferential waves were generated automatically in the shell and in the water-shell interface (Symmetric waves S_i and Antisymmetric waves A_i). For some frequencies, these circumferential waves make standing waves on the circumference of the shell constituting resonances [1, 2, 3, 4, 5, 6]. These resonances are observed in the spectrum of the scattering acoustic pressure. The previous studies shows that the acoustic resonances of the shell are related to its physical and geometrical proprieties [7, 8, 9, 10]. Some of these studies, done on submerged air-filled cylindrical and spherical shells, have shown the bifurcation of the dispersion curve for the guided wave A_0 wave into two waves denoted by A_0- and A_0+ [11, 12]. Works in Refs. [13, 14] are concerned with the acoustic scattering from polymer coupled with a thin layer of water or from cylindrical shells filled with water. Furthermore, some research has investigated the acoustic scattering from bi-layered cylindrical shells and multi-layered spherical curved plates [15, 16, 17].

In the first part of this work, we focused on study of the acoustic scattering by an air-filled stainless steel-copper and copper-stainless steel bi-layered cylindrical shells immersed in water. The stainless steel and copper one-layered cylindrical shells are taken as a reference for studying the acoustic scattering from bi-layered cylindrical shells. This paper reveals the effect of physical and geometrical characteristics of the layers constituting the shells on the scattering phenomenon. The work is done from the calculated form function, the obtained resonance trajectories have shown the changes appeared on the guided waves. In this research, we investigate the resonance trajectories of symmetrical and anti-symmetrical guided waves, especially the curves change. The findings are compared with those obtained for the stainless steel and copper mono-layered cylindrical shells.

In the second part, we focus on investigation the reduced cut-off frequencies of circumferential A_1 wave, that have been extracted for different possible values of the intermediary radius. This treatment is done for three cases of bi-layered cylindrical shells; copper/stainless steel, aluminum/stainless steel and copper/aluminum, in the object to have a good understanding of the observed phenomena.

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For copper/stainless steel coupling, the results show the sliding of the reduced cut-off frequencies of A_1 guided wave towards low values and to higher values when layers order change. For aluminum/stainless steel and copper/aluminum coupling, the reduced cut-off frequencies values change in an oscillating form. Evaluations made on reduced cutoff frequencies of A_1 wave, reveals the process of the repulsion, the interaction and the coupling of guided waves phenomena. That is carried out because the wave propagation in the composite cylinder is sophisticated because of the heterogeneity of the compositions, and the intrinsic anisotropy of the layer materials, which results in the speeds of the guided wave modes, circumference order number, frequency, and inter-layer interface conditions.

2. Acoustic scattering from cylindrical shell

2.1. Theoretical study

If an air filled multi-layered elastic cylindrical shell made in a given material immersed in water and excited by a plane acoustic wave, several waves are generated in and around the shell. Figure 1 shows the cylindrical shell and the direction of the incident plane wave, with a: outer radius, b: intermediary radius and c: inner radius. (x, y, z) is the Cartesian coordinate system with origin at O, the z-axis is coincident with the axis of the cylindrical shell. The corresponding cylindrical coordinate system (r, θ, z) associated to the considered structure is chosen [18, 19, 20, 21].

The acoustic pressure of the incident plane wave in medium 1, denoted by $P_{inc}(\omega, \theta, r)$, can be written in cylindrical coordinate as

$$P_{inc}(\omega, \theta, r) = P_0 \sum_{n=0}^{+\infty} j^n \varepsilon_n J_n(k_1 r) \cos(n\theta) \exp(-\mathrm{j}\omega t), \quad (1)$$

where P_0: amplitude of the incident plane wave, $J_n(k_1 r)$ is the Bessel function of the first kind of order n, ω is the angular frequency, $k_1 = \omega/C_1$ is the wave number with C_1 is the wave velocity in the external fluid, ε_n is the Neumann coefficient ($\varepsilon_n = 1$ if $n = 0$ and $\varepsilon_n = 2$ if $n \neq 0$), $j^2 = -1$, θ is the azimuthal angle and r is the distance between the position where the pressure is calculated and the revolution axis of the cylindrical shell. The pressure of the scattered waves can be expressed as

$$P_{scat}(\omega, \theta, r) = P_0 \sum_{n=0}^{+\infty} j^n b_n H_n^1(k_1 r) \cos(n\theta) \cdot \exp(-\mathrm{j}\omega t), \quad (2)$$

where $b_n = D_n^1(\omega)/D_n(\omega)$ is the coefficient which characterizes the acoustic scattering in medium 1, $D_n^1(\omega)$ and $D_n(\omega)$ are two determinants computed from the boundary conditions of the problem [2, 21], and $H_n^1(k_1 r)$ is the Hankel function of the first kind of order n.

To describe the acoustic scattering from a cylindrical shell, we use the form function. The expression of this function in a far field is given by [18, 19, 20, 21]

$$F_\infty(x_1, \theta) = \left| f_\infty(x_1, \theta) \right| \approx \lim_{r \to +\infty} \sqrt{\frac{2r}{a}} \left| \frac{p_{scat}}{p_{inc}} \right|, \quad (3)$$

$$F_\infty(x_1, \theta) \approx \left| \sum_{n=0}^{+\infty} f_n(x_1, \theta) \right|, \quad (4)$$

where $x_1 = k_1 a$ is the reduced frequency which is the number of wavelengths of the acoustic wave, propagating in the external medium (medium 1), included the circumference of the cylindrical shell, it is written as follows: $k_1 a = 2\pi a/\lambda_1$.

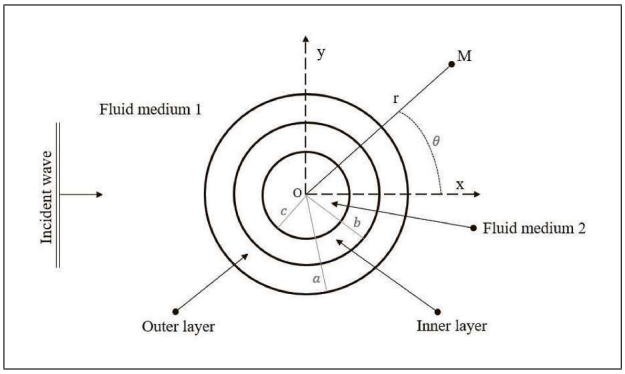


Figure 1. The geometry used for formulating the scattering pressure by an elastic cylindrical shell.

Table I. Physical parameters. Density ρ (Kg/m^3), longitudinal velocity C_l (m/s), transvers velocity C_t (m/s).

	ρ	C_l	C_t
Aluminum	2800	6320	3070
Stainless steel	7900	5790	3100
Copper	8920	4760	2325
Watter	1000	1470	–
Air	1.29	324	–

2.2. Form function

The bi-layered cylindrical shells comprise an outer layer in contact with water, and a layer on the inner part in contact with air in the cavity. The mono-layered cylindrical shells comprise one layer on contact with water on the outer, and air in the cavity. These cylindrical shells are characterized by the same geometric properties; for bi-layered cylindrical shells, the outer radius $a = 1$ cm, the intermediary radius 0.94 cm $< b < 1$ cm and inner radius $c = 0.94$ cm, for mono-layered cylindrical shells, the outer radius is equal to 1 cm, and the inner radius is equal to 0.94 cm. In this work we treat three examples of bi-layered cylindrical shells; copper/stainless steel, aluminum/stainless steel and copper/aluminum. For the mono-layered cylindrical shells are made of copper, stainless steel and aluminum. The physical parameters of the studied cylindrical shells are illustrated in Table I.

The form function is computed in a far field for $\theta = \pi$ as a function of the reduced frequencies x_1 ranging from

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0.1 to 250. In the calculations, the bandwidth of the transducer is considered. Figure 2 presents the form function for stainless steel-copper bi-layered cylindrical shell with $b = 0.97$ cm. Many amplitude variations due to the presence of various resonances are observed in the form functions.

2.3. Resonance spectrum and resonance trajectories

When a circumferential wave is generated, the resonances are observed when the number of wavelengths on the circumference of the shell is an integer; this integer is the mode n [1]. The observed spectrum of resonances results from the inverse Fourier transform of the form function which is the summation of the vibration modes n for each frequency. The plane of modal identification is an alternative representation of this spectrum [4]. Each horizontal line of this plane is the contribution of a single mode obtained from the partial form function f_n [22, 23, 26].

To obtain the resonance spectrum, we start firstly by computing the time signal with an Inverse Fourier Transform of the form function [12]. Then, the specular echo which is related to the reflexion on the outer surface of the shell is suppressed and replaced by zeros. A Direct Fourier Transform is applied to this new time signal to obtain the resonance spectrum [25]. Figure 3 represents the resonance spectrum of stainless steel-copper bi-layered cylindrical shell with radius $b = 0.97$ cm.

The same procedure was applied to the partial form function in order to obtain the resonance trajectories of vibration modes. The resonance spectrum is calculated for each value of mode n. After that the partial resonance spectrum are assembled in a matrix. The representation of this matrix includes several trajectories. Each trajectory is linked to a wave type. Some trajectories have a reduced cut-off frequency for the small values of the mode n. In Figure 4, the resonance trajectories are presented for stainless steel-copper bi-layered cylindrical shell with $b = 0.97$ cm. This figure shows that the resonance trajectory of the A_0 wave is bifurcated into A_0- and A_0+. This results is similar to that observed in the case of mono-layered cylindrical and spherical shells [11, 3, 12]. The reduced cut-off frequency of A_1 wave is indicated by an asymptotic line and its value is close to 93.8.

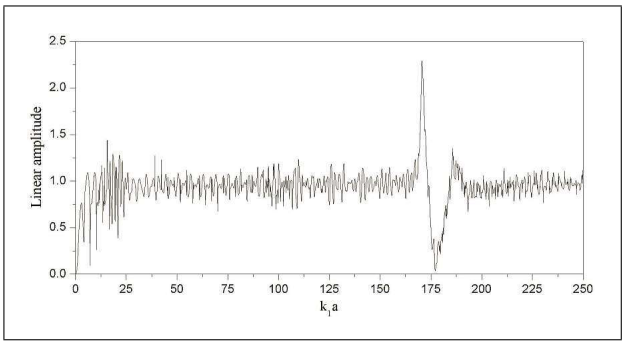


Figure 2. Form function of stainless steel-copper bi-layered cylindrical shell with $b = 0.97$ cm.

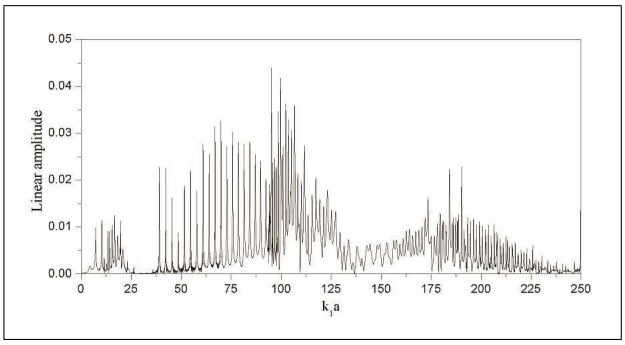


Figure 3. Resonance spectrum of stainless steel-copper bi-layered cylindrical shell with $b = 0.97$ cm.

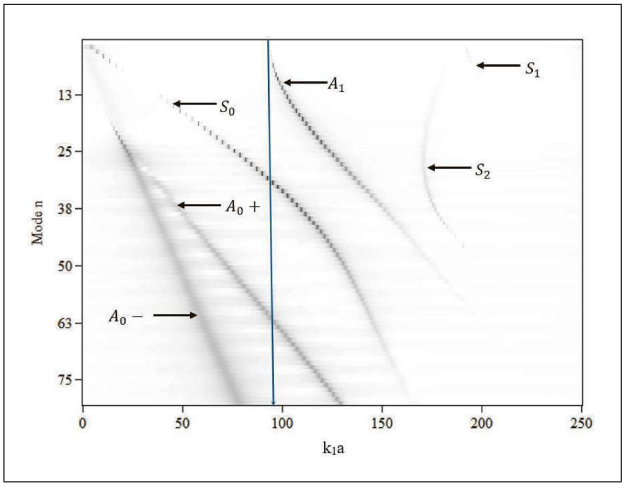


Figure 4. Resonance trajectories of stainless steel-copper bi-layered cylindrical shell with $b = 0.97$ cm.

3. Results and discussion

3.1. Comparison the resonance trajectories of the mono-layered and bi-layered cylindrical shells

The resonance trajectories for the mono-layered stainless steel and copper cylindrical shells and the bi-layered stainless steel-copper and copper-stainless steel cylindrical shells are presented in the same graphic Figures 5 and 6, respectively.

The comparison of different resonance trajectories leads us to conclude a number of remarks:

- The resonance trajectories of the mono-layered stainless steel cylindrical shell are close to those of the bi-layered stainless steel- copper with $b = 0.941$ cm (Figure 5). However, those of the mono-layered copper cylindrical shell are close to those of the bi-layered copper-stainless steel with $b = 0.941$ cm (Figure 6).
- The A_0+ wave resonance trajectories are sensitive to the intermediary radius b, of the cylindrical shells, a gradual deviation of the trajectory are noted.
- However, the A_0- wave resonance trajectories are not sensitive to the physicals properties of the shells. This can be explained by the fact that the main support of this wave is the external medium [11, 3, 12].

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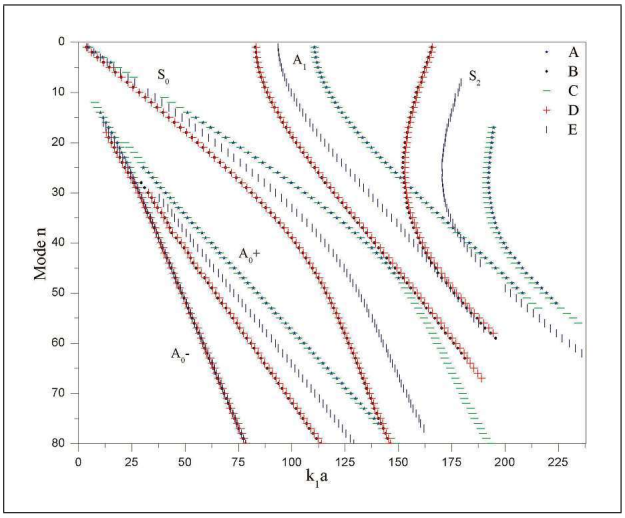


Figure 5. Comparison between resonance trajectories of the studied cylindrical shells; A: mono-layered stainless steel, B: mono-layered copper, C: copper-stainless steel bi-layered with b = 0.999 cm, D: copper-stainless steel bi-layered with b = 0.941 cm and E: copper-stainless steel bi-layered with b = 0.97 cm.

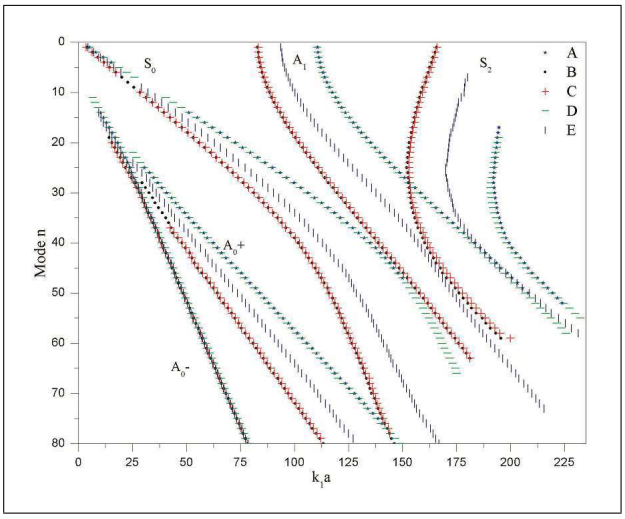


Figure 6. Comparison between resonance trajectories of the studied cylindrical shells; A: mono-layered stainless steel, B: mono-layered copper, C: stainless steel-copper bi-layered with b = 0.941 cm, D: stainless steel-copper bi-layered with b = 0.999 cm and E: stainless steel-copper bi-layered with b = 0.97 cm.

- The S_0 wave resonance trajectories of different cylindrical shell are close to each others for the mode n is inferior to 10. However, a gradual deviation of different trajectories is noted when the mode n is superior to 10.
- The resonance trajectories of the A_1 waves for stainless steel-copper and copper-stainless steel bi-layered cylindrical shells are localized between the resonance trajectories of the A_1 wave for the stainless steel and copper mono-layered cylindrical shells. These trajectories have a reduced cut-off frequency which is close to 110.7 for the mono-layered stainless steel cylindrical shell, close to 82.9 for the mono-layered copper cylindrical shell. For copper-stainless steel bi-layered cylindrical shells, Figure 5 shows that the trajectory of the A_1 wave has a value of the reduced cut-off frequency close to 83.1, when the intermediate radius b equal to 0.941 cm, close to 93.8 when b = 0.97 cm, and close to 110.3 when b = 0.999 cm. For stainless steel- copper bi-layered cylindrical shells, Figure 6 shows that the A_1 wave trajectory has a reduced cut-off frequency close to 110.4 for the intermediate radius b = 0.941 cm, close to 93.8 when b = 0.97 cm, and close to 83.3 when b = 0.999 cm. We can see that for bi-layered cylindrical shells this value is varied with the intermediary radius b. In the next section for more understanding, this work is completed by an investigation on the reduced cut-off frequencies of the A_1 wave, that have been extracted for different possible values of the intermediary radius.
- The resonance trajectories of the S_2 waves for stainless steel-copper and copper-stainless steel bi-layered cylindrical shells are localized between the resonance trajectories of the S_2 wave for the stainless steel and copper mono-layered cylindrical shells.

Table II. Acoustic impedance Z and reduced cut-off frequencies f_r of the A_1 wave for mono-layered cylindrical shells b/a = 0.94.

	Z	f_r
Aluminum	17.60	109.5
Stainless steel	45.70	110.7
Copper	41.61	82.9

3.2. Analysis of the reduced cut-off frequency of the circumferential wave A_1

In this part, we focus on investigation the reduced cut-off frequencies of circumferential A_1 wave, that have been extracted for different possible values of the intermediary radius. This treatment is done for three cases of bi-layered cylindrical shells. The choice of combined materials is based on acoustic impedance contrast. For copper/stainless steel coupling is characterized by low impedance contrast; copper/aluminum coupling is characterized by higher impedance contrast; and aluminum/stainless steel coupling is also characterized by higher impedance contrast, and the value of the reduced cut-off frequencies of the A_1 wave for aluminum and stainless steel mono-layered cylindrical shells taken as reference are close to each other Table II.

3.2.1. Case 1: copper/stainless steel

The evolution of the reduced cut-off frequencies of the A_1 wave for copper-stainless steel bi-layered cylindrical shell are presented as a function of the values of the intermediate radius b in Figure 7. When b increased, the thickness of the inner layer (stainless steel) increases and the thickness of the outer layer (copper) decreases, the reduced cut-off frequency of the A_1 wave is varied. This variation follows the evolution of hyperbolic function in ascending order. However, for stainless steel-copper bi-layered cylindrical shell the evolution of the reduced cut-off frequency

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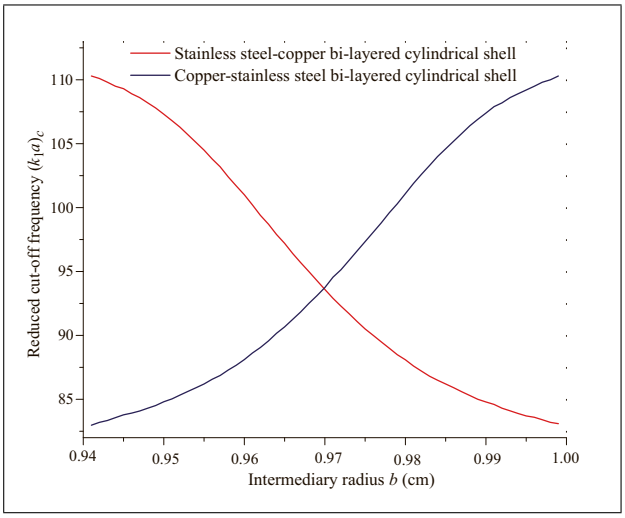


Figure 7. Evolution of the reduced cut-off frequency of the A_1 wave as a function of the intermediate radius b for the copper-stainless steel and stainless steel-copper bi-layered cylindrical shells.

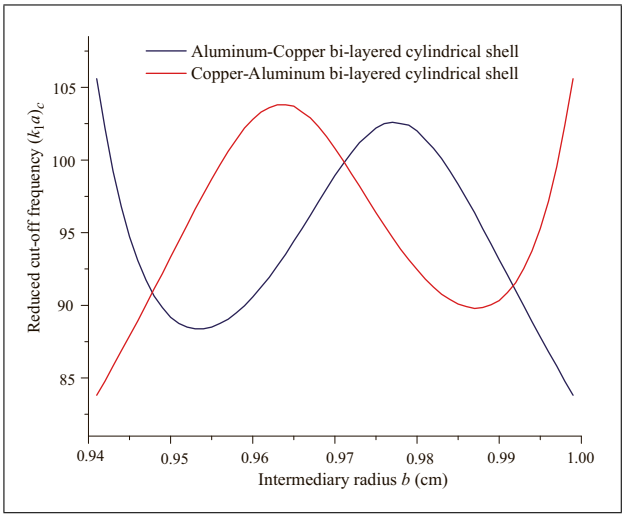


Figure 8. Evolution of the reduced cut-off frequency of the A_1 wave as a function of the intermediate radius b for the copper-aluminum and aluminum-copper bi-layered cylindrical shells.

of the A_1 wave is presented in Figure 7. When b increased, the thickness of the inner layer (copper) increases and the thickness of the outer layer (stainless steel) decreases, the evolution of the reduced cut-off frequency of the A_1 follows the evolution of a hyperbolic function in descending order. The obtained values are compared with the values obtained for mono-layered stainless steel and copper cylindrical shells which is close to 110.7 for a stainless steel cylindrical shell ($b/a = 0.94$), and is close to 82.9 for a copper cylindrical shell ($b/a = 0.94$). In this case, the values of reduced cut-off frequency of A_1 wave for bi-layered cylindrical shells are varied between the values obtained for stainless steel and copper mono-layered cylindrical shells whatever the value of intermediary radius b.

3.2.2. Case 2: copper/aluminum

The evolution of the reduced cut-off frequencies of the A_1 wave for copper-aluminum bi-layered cylindrical shell are presented in Figure 8. When b increased, the thickness of the inner layer (aluminum) increases and the thickness of the outer layer (copper) decreases, the reduced cut-off frequency of the A_1 wave is changing. For $b = 0.941$ cm the A_1 wave has a value of the reduced cut-off frequency close to 83.81, When b increased, the value of the reduced cut-off frequency increase until 103.8 for $b = 0.964$ cm, from this point the value of the reduced cut-off frequency decreases until 89.85 for $b = 0.988$ cm and starts to increase again until 105.6 for $b = 0.999$ cm. For aluminum-copper bi-layered cylindrical shell the evolution of the reduced cut-off frequency of the A_1 wave is presented in Figure 8. For $b = 0.941$ cm the A_1 wave has a value of the reduced cut-off frequency close to 105.6, When b increased, the thickness of the inner layer (copper) increases and the thickness of the outer layer (aluminum) decreases; and the value of the reduced cut- off frequency decreases until 88.38 for $b = 0.954$ cm from this point the value of the reduced cut-off frequency increased, until 102.6 for $b = 0.977$ cm and starts to decreases again until 83.81 for $b = 0.999$ cm. The obtained values are compared with those obtained for mono-layered aluminum and copper cylindrical shells Table II. In this case, the values of reduced cut-off frequency of A_1 wave for bi-layered cylindrical shells are varied in oscillating way between the values obtained for aluminum and copper mono-layered cylindrical shells.

3.2.3. Case 3: aluminum/stainless steel

The evolution of the reduced cut-off frequency of the A_1 wave, for stainless steel-aluminum bi-layered cylindrical shell are presented in figure 8. For $b = 0.941$ cm the reduced cut-off frequency of the A_1 wave are close to 111.7. When b increased, the value of the reduced cut-off frequency increase until 128.2 for $b = 0.957$ cm, from this point start to decreases until 92.78 for $b = 0.988$cm and increase again until 106.3 for $b = 0.999$ cm. For aluminum-stainless steel bi- layered cylindrical shell the evolution of the reduced cut-off frequency of the A_1 wave is presented in Figure 8. the reduced cut- off frequency of the A_1 wave are close to 106.3 for $b = 0.941$ cm, when b increased, the value of the reduced cut- off frequency decreases until 91.62 for $b = 0.953$ cm from this point the value start to increased until 127.3 for $b = 0.984$ cm and starts to decreases again until 111.7 for $b = 0.999$ cm. In this case, we have the same observation us in the case of copper-aluminum, the values of reduced cut-off frequency of A_1 wave for bi-layered cylindrical shells are varied in the oscillating way and no longer between the values obtained for aluminum and stainless steel mono-layered cylindrical shells Table II.

3.3. Discussion

In this work, we have studied the case metal-metal in which the both layers are made from metal (copper and

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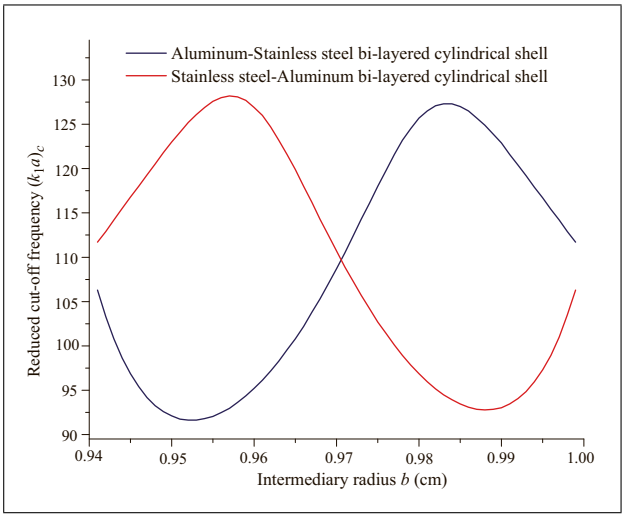


Figure 9. Evolution of the reduced cut-off frequency of the A_1 wave as a function of the intermediate radius b for the aluminum-stainless steel and stainless steel-aluminum bi-layered cylindrical shells.

stainless steel). Comparing the obtained results with the results of previous works obtained in the case of polymer-metal, which is characterized by a strong coupling, noted by the presence of a pseudo wave A_1 [23], and the existence of the waves with the zero group velocity (ZGV waves) [26]. In this study, the thickness of the inner layer plus the thickness of the outer layer is fixed. Therefore, the difference between the resonance trajectories curves of studied bi-layered cylindrical shell can only be attributed to the difference in material properties (density, longitudinal and shear wave velocities) between the inner layer, the outer layer and the thickness ratio between them.

For copper-stainless steel bi-layered cylindrical shell, the effect of the increase of thickness of copper layer on the resonance trajectories curves of the bi-layered cylindrical shell is to move these resonance trajectories curves to the lift direction Figure 5. For stainless steel-copper bi-layered cylindrical shell, The effect of the increase of thickness of stainless steel layer on the resonance trajectories curves of the bi-layered cylindrical shell is to move these resonance trajectories curves to the right direction Figure 6. We can see that if the ratio goes very high for the thickness of the stainless steel layer versus the thickness of the copper layer, the resonance trajectories curves of bi-layered cylindrical shell shift from resonance trajectories of a mono-layered copper cylindrical shell towards the resonance trajectories of a mono-layered stainless steel cylindrical shell, because stainless steel has faster wave velocities than copper. This is manifested on the variations of the reduced cut-off frequency of the A_1 wave Figure 7. The obtained results reveals the existence of a weak coupling outcome from the interaction between the circumferential waves propagating around the shell. This observation has a direct link to their property that are close. Works in [27] confirm this observation that revealed in the case of bi-layered plate.

For aluminum-copper bi-layered cylindrical shell, the effect of the increase of thickness of aluminum layer involved decries of the thickness of copper layer and because of the smaller acoustic impedance of the aluminum, it behaves in the bi-layered cylindrical shell as if it were rigidly held by the copper. The copper layer is responding almost as if it was stress-free on aluminum sides. The copper layer becomes even thinner, so becomes more resonant. Therefore, the resonance curves shift into the right direction. in another hand, increasing of the values of reduced cut-off frequencies of A_1 wave. When thickness ratio between of the aluminum and copper layers become close, this change is reversed in the opposite direction, involved the decrease of the values of reduced cut-off frequencies of A_1 wave. The values of reduced cut-off frequencies of A_1 wave start to increase again, when the thickness of aluminum layer becomes more important than the thickness of the copper layer. We have the opposite of these observations for copper-aluminum bi- layered cylindrical shell. In the last case in which we studied aluminum/stainless steel coupling we have almost the same observations as the copper/aluminum coupling. Except the reduced cut-off frequency of the A_1, that has no longer between the reduced cut-off frequency of the A_1 wave for aluminum and stainless steel mono-layered cylindrical shells.

The obtained results reveals the existence of a strong coupling outcome from the interaction between the circumferential waves propagating around the shell. This phenomenon has a direct link to the interface displacement and stress continuity, because the aluminum has faster wave velocities and a smaller acoustic impedance than copper and stainless steel. This has an effect on the wave propagation into bi-layered cylindrical shell [28]. This current study can help us to understand the acoustic diffusion by coupling metal-metal bi-layered cylindrical shell. On the other hand, if the thickness ratio between layers is fixed, the difference in material properties determines the degree of variation in resonance trajectories curves. Therefore, from the difference in resonance trajectories, one can use the properties of the mono-layered cylindrical shell as a reference to estimate the properties of the bi-layered cylindrical shell.

4. Conclusion

This paper presents a study of the acoustic scattering from bi-layered cylindrical shells filled with air and immersed in water. In object to reveal the effects of physical and geometrical characteristics of the layers constituent the shell on the guided waves. In this work we studied three cases of coupling: copper/stainless steel, aluminum/stainless steel and copper/aluminum. The stainless steel, aluminum and copper mono- layered cylindrical shells are taken as a reference. Moreover, this work focuses on studying the influence of the layer thicknesses and the material in which is made on the circumferential waves. Plane of modal identification was chosen to analyze the scattering phenomenon. The observation of the trajectories of the resonances reveals the existence of a weak coupling which can be ex-

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plained by the interaction between guided waves. This is manifested on the variations of the reduced cut-off frequencies of A_1 wave. The findings are compared with those obtained for the reference cylindrical shells. The finding can help us to understand the acoustic diffusion in the case of metal-metal bi-layered cylindrical shell.

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