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RECOGNITION OF LAYERED STRUCTURE USING PHASE-FREQUENCY CHARACTERISTICS OF RFLECTED SOUND WAVES

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We propose a method for the classification of layered acoustic materials based on sound reflection characteristics. The plate is normally illuminated by a plane sound wave with sweeping frequencies, and the phase of the reflected wave is recorded at each frequency. The phase-frequency features are used to identify a structure among four possibilities. These are single layered, double-layered with harder/softer materials on its front/back and back/front sides respectively, and sandwich structure with a harder material as the outer layers and a softer material in the middle. Numerical simulation shows effectiveness of the method with a high rate of correct classification.

1. Introduction

For a layered plate illuminated by a plane sound wave, there exists close relationship between the layer structure and the characteristics of the reflected echo. This work concerns with classification of layered acoustic materials based on reflection characteristics. However, in a monostatic mode, recognition of the object's interior structure is impossible solely from the amplitude of the echo. Phase information of the reflected wave is necessary. Techniques are available for measuring complex reflection coefficients [1,2], which can be used to obtain the phase of reflected sound. We propose in this paper to use the phase-frequency information in the reflected sound waves to identify the interior structure of several types of layered plates with unknown physical properties.

2. Echoes from layered media

Consider a layered plate normally illuminated by a plane sound wave as shown in Fig. 1. From left to right, each layer has an acoustic impedance Z_1, Z_2, … , and Z_{N+1}, where $Z_n = \rho_n c_n$, with the first and the last layers being water that is semi-infinite in extent. We only consider longitudinal waves in the present work.

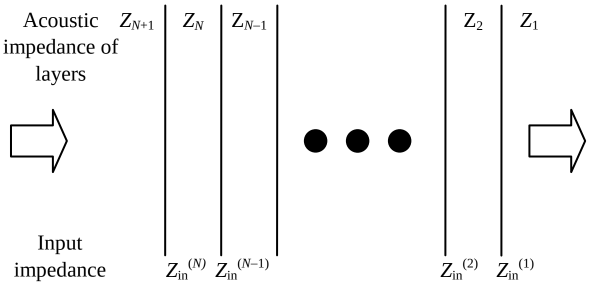


Figure 1. Normal incidence of sound wave on a layered plate.

We can find the input impedance of each layer [3]:

$$Z_{\mathrm{in}}^{(n+1)} = Z_{n+1}\frac{Z_{\mathrm{in}}^{(n)} - jZ_{n+1}\tan\varphi_{n+1}}{Z_{n+1} - jZ_{\mathrm{in}}^{(n)}\tan\varphi_{n+1}}, \quad n = 1, 2, \ldots, N-1 \tag{1}$$

where $\varphi_n = k_n d_n$, $k_n = 2\pi f/c_n$, and d_n is the thickness of the n-th layer. Reflectivity of the plate is:

$$R = \frac{Z_{\mathrm{in}}^{(N)} - Z_{N+1}}{Z_{\mathrm{in}}^{(N)} + Z_{N+1}} \tag{2}$$

From (2), phase of the reflected sound, $\varphi = \arg(R)$, can be obtained, which is a function of the frequency f, and of the density ρ_n, sound speed c_n and thickness d_n of the layers. Methods are available for measuring the complex reflectivity, hence the phase. For example, in a single point measurement scheme [4] as shown in Fig. 2, the complex pressure at the point B is

$$p_B(f) = p_i(f)[1 + \gamma\,|R|\exp(-j2\pi f\tau + j\varphi)] \tag{3}$$

where $|R|$ is the absolute value of the reflectivity, $\gamma = D/(D+2d)$ is a distance modification factor, and $\tau = 2d/c$ is a time delay due to reflection. With the measured $p_B(f)$, the phase can be calculated.

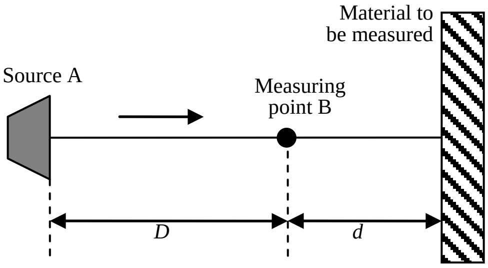


Figure 2. Measuring complex reflectivity.

3. Classification of layered structure based on phase information

Given a layered plate with an unknown structure, the material parameters ρ_n, c_n, and d_n are not available. We illuminate the plate using plane sound waves at a series of frequencies f_m to find the corresponding phase values of the echo. Four types of structures are considered:

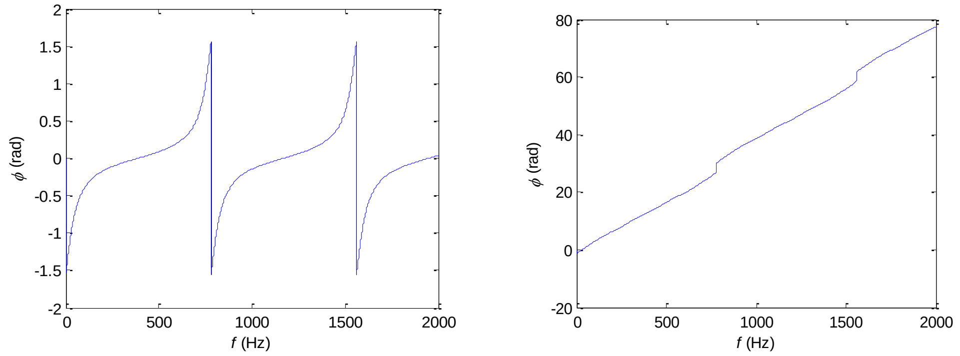
A. Single-layered
B. Double-layered with a harder layer on the front side
C. Double-layered with a softer layer on the front side
D. Triple-layered with the outer layers harder than the inner layer

Being softer or harder means having a smaller or larger ρc value, and all solid materials are harder than water. Based on an analysis on a large amount of numerical results, classification can be made according to the features found in the phase-frequency sequence $\varphi_m(f_m)$ as follows.

1) If the phase of reflectivity oscillates between $-\pi/2$ and $+\pi/2$ as the frequency increases, the plate belongs to type A or B, otherwise it is type C or D, as shown in Fig. 3.

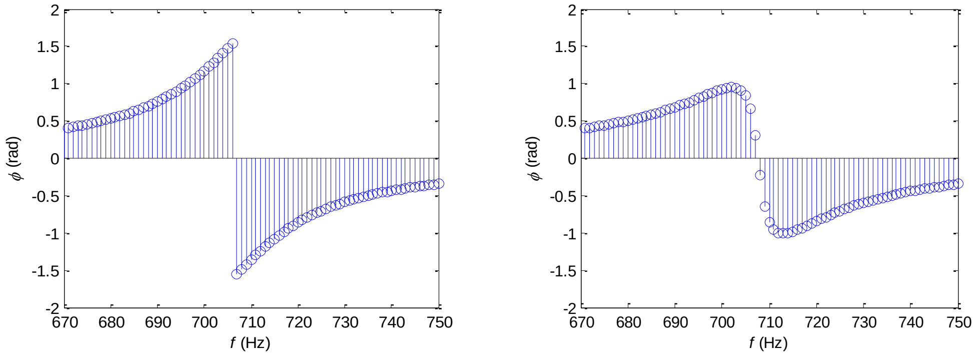
2) For type A, $\tan\varphi = 0$ at $f_m = m(c_2/2d_2)$, $m = 1, 2, 3, \ldots$, making the phase value drop from a positive value to negative abruptly, as shown in Fig. 4(a). For type B, the phase rises monotonically in a range of frequencies without abrupt jumps, see Fig. 4(b). Materials involved in the plots are steel and rubber with densities 7.85g/cm^3 and 1.12g/cm^3, and sound speeds 5200m/s and 1123m/s, respectively.

3) For types C and D, calculate differences of the phase-frequency sequence. For the type C plates, the differences have the same polarity, while that of type D have alternate polarities, as shown in Fig. 5.



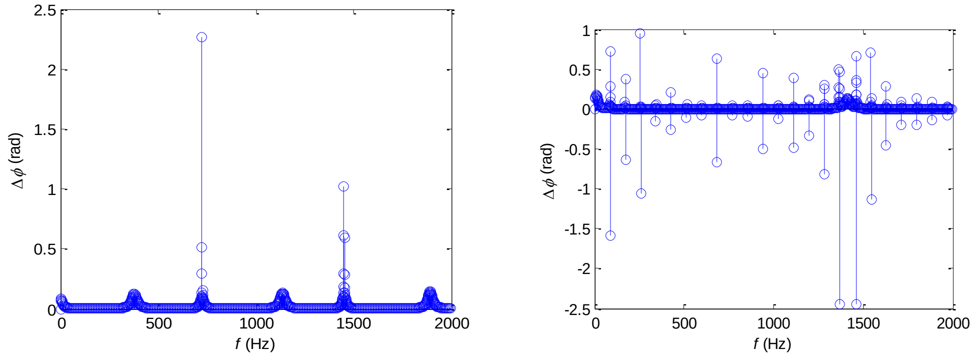
(a) Types A and B (b) Types C and D

Figure 3. Reflectivity as a function of incident wave's frequency.



(a) Single-layered steel (b) Steel on the front, rubber on the back

Figure 4. Classification of structures A and B based on the frequency-phase relationship.



(a) Aluminum on front, steel on back (b) Steel outer layers and water in middle

Figure 5. Classification of structures C and D based on the frequency-phase relationship.

4. Numerical computation

To verify the classification criteria, a large amount of numerical computation is done. In Fig. 6, each point in the ρ-c plane represents a sample of material. The solid and dashed curves correspond to a reference material with impedance $\rho_M c_M$ and materials with the impedance equal to that of water, $\rho_W c_W$, respectively. Randomly choose the values of ρ and c, and let ρ_W=1000g/m^3<ρ <ρ_{max} =10000g/m^3, and c_W=1500m/s<c<c_{max}=10000m/s. Materials harder/softer than the reference should fall into the area to the right/left of the solid curve.

For a double-layered plate, let the tested material be on the front side and a reference material on the back. Decide the type of the structure according to the phase-frequency features as described in Section 2. If it is judged as type C, put a cross at the appropriate place in the ρ-c plane. Put a dot for type B, and a diamond for type A. In case a decision cannot be made, put a triangle. Ideally, all symbols to the right of the solid curve should be dots indicating that the front material is indeed harder. Similarly, all crosses should fall between the solid curve and the dashed curve, and all diamonds on the solid curve. No triangle should appear. Fig. 6 gives two sets of computation results with different ρc values for the reference, showing a high rate of correct identification.

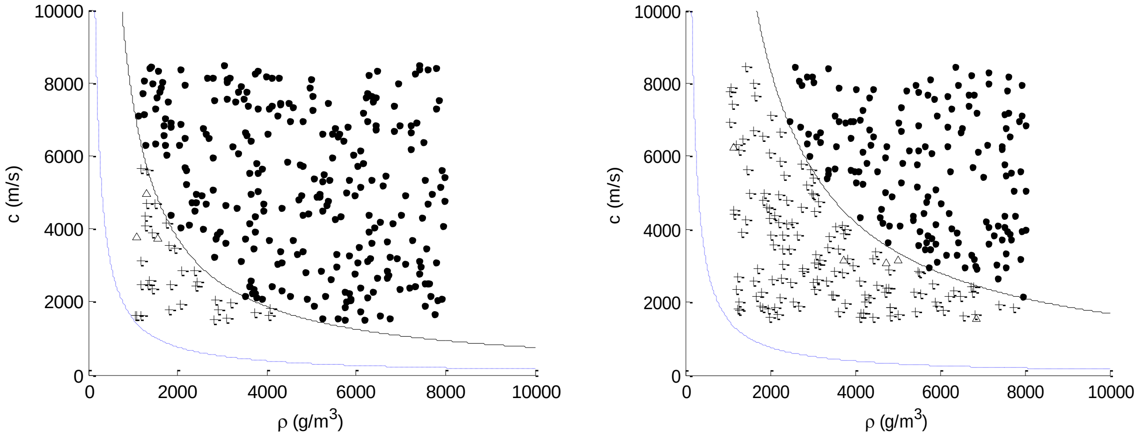


Figure 6. Results of numerical computation for the classification of types A, B and C.

For type D, *i.e.*, the triple-layered structure, the results are plotted in Fig. 7, in which the curve represents ρc values equal to that of the middle layer. Randomly generate materials with ρ_W= 1000g/m^3<ρ<ρ_{max}= 10000g/m^3, and c_W=1500m/s<c< c_{max}=10000m/s. By using the criteria given in the previous section, put a dot if the structure is judged as a sandwich, otherwise plot a cross. It is seen that for materials with c<8000m/s, the rate of correct judgment approaches 100%, while for larger c, the method becomes inapplicable.

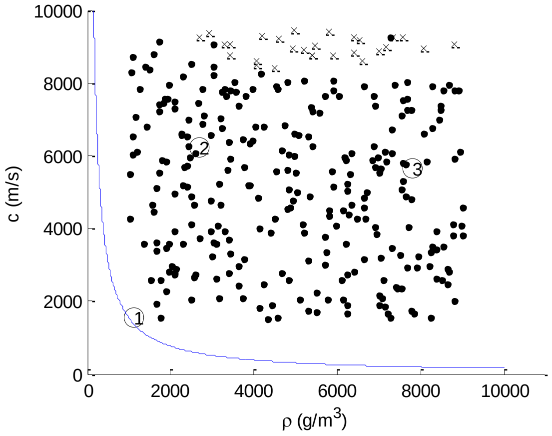


Figure 7. Results of numerical computation for type D.

5. Conclusions

We propose a method to classify layered plates based on the phase-frequency characteristics of the reflected echoes with a plane sound wave incident perpendicularly on the plate. Four types of layered structures can be identified, including single layered plates, double-layered plates with a softer/harder material on the front side, and triple-layered plates. The method does not rely on the amplitude of the echo. The physical mechanism needs to be further studied, which may lead to improved performance and practicality.

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