Acoustic performance of locally resonant layer backing with panel-water-panel termination

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Abstract: The acoustic performance of locally resonant layer backing with the “panel-water-panel” termination has been studied. Using the finite element software COMSOL, the acoustic model of locally resonant layer has been given firstly. Then, the effect of several parameters including incident angles, cell numbers and cavity defects, on the sound absorption performance of locally resonant layer have been numerically analyzed.

Keywords: Acoustic Performance; Locally resonant layer; Oblique incidence; Cavity defect

1. Introduction
Locally resonant acoustic metamaterials are based on artificial periodic materials from sonic crystals. Usually, some cells which can be solid or liquid are distributed periodically in sonic crystals, so the parameters of different cells such as elastic constant and mass density are periodically alternated. In 1992, Sigalas [1] used spherical scatters to embed in a matrix to form a three-dimensional periodic lattice structure, and confirmed the existence of elastic band gaps for the first time theoretically. In 2013, Hwan [2] studied the attenuation and dissipation of acoustic waves in viscoelastic acoustic metamaterials which are composed of air and metal units. Based on the acoustic metamaterial which contains periodic criss-crossed elliptical holes, the band gap can be moved through altering the long and the short radii of elliptical hole by Gao [3]. Based on the extended transfer matrix method, Ansari [4] improved the wave propagation characteristics of sonic crystals by altering the band gap of the magnetoelastic material. Lü [5] studied the low-frequency sound absorption performance of the viscoelastic coating with different embedded scatterers.

At present, researches about locally resonant materials mostly focused on the infinite periodic structure, and the effect of material and structural parameters of cells on the band gap has been discussed mainly. But, there are not many studies concerning locally resonant materials used for the underwater sound absorption and noise reduction. In practical applications, it is impossible to get an locally resonant layer with an infinite thickness, and the acoustic performance of the locally resonant layer in a wider frequency range should be concerned, which was not covered in previous studies. Thus, the acoustic performance of a two-dimensional three-component locally resonant layer with a finite length under oblique incidence condition of plane wave is studied by the finite element software COMSOL in the next section.

2. Locally resonant layer
Figure 1 shows a two-dimensional three-component periodic locally resonant cell. As shown in the figure, component 1, 2 and 3 are the coating made of silicon rubber, the oscillator made of lead and the matrix made of epoxy resin respectively. The densities are \( \rho_1 = 1300 \, \text{kg/m}^3 \), \( \rho_2 \), \( \rho_3 \).
11600 kg/m³, 1180 kg/m³, \((i = 1, 2, 3)\), where subscript 1, 2, 3 indicates to silicon rubber, lead and epoxy resin respectively. Besides, the three Lame constants are \(\lambda_i = 0.6\) MPa, 42.3 GPa, 4.43 GPa \((i = 1, 2, 3)\), and the shear moduli are \(\mu_i = 0.04\) MPa, 14.9 GPa, 1.59 GPa \((i = 1, 2, 3)\), respectively. Moreover, the outer and inner radii \((r_1, r_2)\) of component1 are 6mm and 4mm respectively, and the length \(H\) of locally resonant cell is 14mm. The selection of materials of locally resonant layer is based on the Hou’s research [6], but structural parameters have been changed in this paper. It should be noted that Hou focused on the infinite periodic structure mainly, while the finite one is taken as the study object in this paper.

![Schematic diagram of locally resonant cell](image)

**Figure 1.** Schematic diagram of locally resonant cell

Figure 2 shows a model used to predict the underwater acoustic performance of a finite locally resonant layer whose thickness is 10 locally resonant cells. As shown in the figure, the perfect matching layer, the incident water region, the locally resonant layer, the steel panel 1, the intermediate water region and the steel panel 2 are fixed from left to right in the model. The thicknesses of steel panel 1, 2 and intermediate water are 6mm, 6mm and 180mm respectively.

![Prediction model of acoustic performance of locally resonant layer](image)

**Figure 2.** Prediction model of acoustic performance of locally resonant layer

### 3. Acoustic performance analysis of locally resonant layer

When the plane wave impinges normally on the locally resonant layer from the incident water, sound reflection coefficient and absorption coefficient of the locally resonant layer are shown in Figure 3. Because of the modulation of the intermediate water layer, the two curves of reflection coefficient and absorption coefficient show an obvious fluctuation with the increase of frequency.

Figure 4 compares the displacement fields of the locally resonant layer at the first peak frequency (600Hz) and the first trough frequency of absorption (2300Hz). As shown in the figure, the overall displacement of locally resonant layer at 600 Hz is obviously higher than the one at 2300 Hz: (1) at 600 Hz, vertical vibration of each resonant cell from top (the first one) to bottom (the tenth one) can be distinctly observed, and the maximum displacement whose value is up to \(1.68 \times 10^{-7}\)m happens around the oscillator of the first resonant cell; (2) at 2300 Hz, the relatively obvious transverse vibration only can be found around the upper five resonant cells, and the displacement amplitude decreases significantly. Thus, if the displacement amplitude is higher and the numbers of vibrating
cells is more, the friction between the oscillator, coating and matrix will be intenser, which will cause more loss of acoustic energy.

![Figure 3. Acoustic performance of the locally resonant layer](image)

Figure 3. Acoustic performance of the locally resonant layer

![Figure 4. Displacement fields at 600Hz (left) and 2300Hz (right)](image)

Figure 4. Displacement fields at 600Hz (left) and 2300Hz (right)

3.1. Effect of incident angle

Figure 5 compares the sound absorption coefficients of locally resonant layer under at different incident angles of plane waves. When the frequency is below 1000Hz, the change of incident angle has little influence on the sound absorption performance. With the increase of frequency, the sound absorption performance under normal incidence is better than those under other incident angles. Besides, the frequency of sound absorption coefficient at the peak will shift to a higher frequency if the incident angle increases.
Figure 5. Effect of different incident angles on sound absorption coefficient of locally resonant layer.

Figure 6. Displacement field at the first absorption peak frequencies under different incident angles.

Figure 6 shows the displacement fields of locally resonant layer at the first absorption peak frequencies (about 600, 600, 600 and 500Hz, because the frequency step is 100Hz in the acoustic simulation) under corresponding different incident angles (0°, 30°, 45° and 60°). As shown in the figure, the displacement fields of locally resonant layer are basically same under four different incident angles, only the location and the amplitude of the maximum and the minimum displacements are slightly different.

Figure 7 shows the energy loss of locally resonant layer at the first absorption peak frequencies under the corresponding different incident angles. It can be found that the energy loss is dominantly concentrated in the silicon rubber because of the vertical vibration of the oscillator. Since the incident energy will reflect mostly on the bottom surface of locally resonant layer because of the adjacent steel panel, and the more energy will accumulate and lose around the bottom of the locally resonant layer, so the maximum energy losses are all near the bottom oscillator at four incident angles.
Figure 7. Energy loss at the first absorption peak frequencies under different incident angles

3.2. Effect of cell number

The effect of the cell number (N = 1, 5, 10 and 15) on the acoustic performance of a locally resonant layer is shown in Figure 8, where other material properties and structural parameters remain unchanged. With the increase of cell number, the sound absorption performance of locally resonant layer improves greatly in the whole frequency range, especially in the low and the medium frequency ranges, and the frequency at the absorption peak shifts to a lower frequency. The sound absorption coefficients of 15 cells are over 0.75 in the whole frequency range, which is far more than the coefficients of 1 cell.

Figure 8. The effect of the number of cells on the acoustic performance

Figure 9 shows displacement fields of the locally resonant layer with different cell numbers at the second absorption peak frequency. As shown in Figure 9(c) and 9(d), the resonance of the whole layer mainly concentrates in the first five cells (from the top). When there is only one cell in the locally resonant layer, the energy loss is relatively lower, which leads to a smaller sound absorption coefficient. When cell number exceeds five, although the cell at the bottom of locally resonant layer vibrates as well, the amplitude is obviously weaker than the situation that cell number is 5, and the energy loss is very limited. Therefore, the improvement of sound absorption coefficient is very limited when the cell number increases to more than 5.
3.3. Effect of cavity defect

It has been confirmed that the bandgap characteristics will be changed if some defects occur in an infinite periodic structure [7-8]. Taking account of 10-cell locally resonant layer shown in Figure 2, the lead oscillator of the first and fifth cells from the top (the incident side) are replaced by air to form two different locally resonant layers with cavity defects. Figure 10 shows the effect of cavity defects on the acoustic performance of locally resonant layer under the incident angle 30 degree. In this figure, the sound absorption coefficient of locally resonant layer which contains 10 alternately ordered oscillator units (lead-air-lead-air) is shown as green dotted lines.

As shown in the figure, the sound absorption performance in the frequency range from 2100Hz to 3000Hz gets improved due to the existence of cavity defects. Compared with other defect forms, the layer in the alternate airholes defect form gets the best improvement of sound absorption from 2100Hz to 3400Hz. In the frequency range from 3400Hz to 4600Hz, only the sound absorption performance of locally resonant layer with the first cavity defects has improved, but the range of improvement is not very wide. It can be concluded that the sound absorption performance of locally resonant layer in some frequency range will get improved if the oscillator changes from heavy lead to air.

4. Conclusion

Based on the numerical model of locally resonant layer, the acoustic performance of a two-dimensional three-component locally resonant layer with finite thickness has been analyzed, and some results are concluded as follows:

Figure 9. Displacement field at the second absorption peak frequencies

Figure 10. The effect of cavity defect on the acoustic performance
• For the plane in band-gap frequency range, the locally resonant layer with finite thickness can not completely block the wave propagating, but still can isolate most of the wave energy.
• As the cell number increases, the sound absorption performance of locally resonant layer gets improved effectively in the whole frequency range, especially in the low and the medium frequency ranges, and the frequency at the absorption peak shifts to a lower frequency.
• For finite locally resonant layer, the cavity defect can alternate the resonance characteristic and affect the acoustic performance of locally resonant layer in some frequency range and the range of improvement is not very wide.

5. References
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