Numerical analysis and experimental study of sound insulation performance of underwater viscoelastic coated compound structures

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Abstract: Based on wave transfer propagation theory in infinite layered medium, sound insulation performance for underwater compound damping structures (basic materials are rubber and steel) is investigated using transfer matrix method and percentage distribution of sound energy in certain area. Simulations show that the property of rubber material influences sound insulation of structure greatly. Soft rubber as well as those with small Poisson’s ratio may improve sound insulation performance of the whole structure remarkably. Multi-layered rubber compound structures outperform mono-layered ones. It’s a good way to make cavities inside multi-layered rubber compound structures for improving sound insulation property. The more the cavities are, the better sound insulation will achieve. As a particular kind of complex multilayered rubber compound structures, honeycomb sandwich rubber compound structure has better sound insulation property than rubber interlayer with cylindrical cavities compound structure and homogeneous rubber compound structure. To confirm theoretical analysis, many measurements of freedom-field of honeycomb sandwich compound structure have been carried out in anechoic water tank. The measurement results have good agreement with theoretical prediction.

Key words: visco-elastic material; sound insulation; compound structure; honeycomb sandwich; freedom-field measurement; anechoic water tank

1 INTRODUCTION

Viscoelastic damping materials have been widely used in many areas involving the coating of water-borne structure to reduce the acoustic echo to avoid active sonar systems. As a particular kind of damping material, rubber has lower Young’s modulus and better strain recovery ability compared with metal material, and so it can prevent structure from vibration and noise transmitting more effectively. In this paper, the study of sound insulation performance of underwater compound damping structures (basic materials are rubber and steel) is made, which can provide a guidance for underwater structures’ sound insulation research and its engineering applications.

There are four important analysis methods for sound source transmission loss (SSTL); transfer matrix method (TMM), finite element method (FEM), boundary element method (BEM) and statistical energy analysis (SEA). TMM is a classical approach to solve SSTL, which is adopted in literatures [1-2]. The results of literatures [1-2] show that there are some differences between predicted values and measuring ones in low frequency range because the infinite plate theory does not consider the influence of geometrical dimensions. But the limitation can be modified in a certain extent by considering structure finite sizes. SEA method in literature [3] can simplify complex vibration-acoustic damping system and change its energy transmission to a set of linear equations’ solution. But in gen-
eral. SEA is commonly applied to calculate SSTL for high frequencies and it is also limited when solving non-resonance problems of sound and energy. Numerical method referred in literature[4] is not restricted by structure geometrical dimensions and material properties, and can be applied to solve non-linear problems. But when the frequency increases, division mesh number manifolds rapidly, calculating the highest frequency is then confined. To break the limitations of single approaches, combination of two kinds of methods is considered. For instance, FEM with BEM is used to treat with low frequency diffusing field SSTL of double-wall sound barriers with elastic porous linings in literature[5]; while the combination of FEM and SEA is used to dispose SSTL of multilayered panels in literature[6]. But there are some problems in the combinations. Comparatively, TMM is the better method, which has a long investigation history and mature theory analysis.

Therefore, based on wave transfer theory of infinite layered medium in literature[7], transfer matrices and sound energy average on cross section are adopted as theoretical analysis methods. Firstly, in condition of normal incidence, the sound insulation performance of homogeneous underwater coatings is studied and the shortages in frequency response properties are pointed out. Furthermore, the sound insulation mechanism of underwater coatings containing uniform cylindrical cavities is analyzed. A new type of underwater sound insulation coatings is proposed and named as honeycomb sandwich compound structure, its sound insulation performances are also investigated. To confirm theoretical analysis, large sample freedom-field measurement of honeycomb sandwich compound structure is researched in anechoic water tank. In the trails, the measurement system based on B&K3560C, computer and pulse software are adopted. Meanwhile, a series of methods based on national freedom-field measurement standard are used to improve measurement precision in low frequency range. The measurement results are in good agreement with theoretical prediction. The theoretical formulation and results are described in Sec.2, the results obtained with different structures(RCS, RIWCCS) are shown and discussed in Sec.3.
When \( x=d_1 \),
\[
\begin{bmatrix}
-e^{-jk_1d_1} & e^{jk_1d_1} \\
-e^{-jk_1d_1} & -e^{jk_1d_1}
\end{bmatrix}
\begin{bmatrix}
P_{2i} \\
P_{2r}
\end{bmatrix}
=
\begin{bmatrix}
-z_{12}e^{-jk_1d_1} & -z_{12}e^{jk_1d_1}
\end{bmatrix}
\begin{bmatrix}
P_{1i} \\
P_{1r}
\end{bmatrix}
\tag{5}
\]

When \( x=d_1+d_2 \),
\[
\begin{bmatrix}
-e^{-jk_1d_1} & e^{jk_1d_1} \\
-e^{-jk_1d_1} & -e^{jk_1d_1}
\end{bmatrix}
\begin{bmatrix}
P_{2i} \\
P_{2r}
\end{bmatrix}
=
\begin{bmatrix}
-e^{-jk_1(d_1+d_2)} & e^{jk_1(d_1+d_2)} \\
-e^{-jk_1(d_1+d_2)} & -e^{jk_1(d_1+d_2)}
\end{bmatrix}
\begin{bmatrix}
P_{1i} \\
P_{1r}
\end{bmatrix}
\tag{6}
\]

where \( k_l (l=0,1,2) \) represents wave number in water, rubber and steel layer, respectively; \( k_3=k_0 \) represents wave number in water layer. \( z_{10}, \ z_{12} \) and \( z_{23} \) represent impedance ratio of water/rubber, rubber/steel and steel/water, respectively. \( d_1 \) and \( d_2 \) are thickness of rubber layer and steel plate, respectively.

Rubber is a kind of viscoelastic material, and wave number in rubber panel \( k_1 \) is a complex value, which can be calculated by

\[
\tilde{E}=E(1+j\eta)
\]

\[
\lambda=\frac{E\sigma}{(1+\sigma)(1-2\sigma)}
\]

\[
\mu=\frac{E}{2(1+\sigma)}
\]

\[
\tilde{c}=\sqrt{\frac{\lambda+2\mu}{\rho}}
\]

\[
k_1=\frac{\omega}{\tilde{c}}
\]

where \( \tilde{E} \) is complex modulus of rubber; \( \lambda \) and \( \mu \) are two Lame parameters, \( \tilde{c} \) is longitudinal wave’s complex sound velocity in rubber, \( E, \eta, \sigma \) and \( \rho \) are Young’s modulus, loss factor, Poisson’s ratio and density of rubber, respectively.

### 2.2 Sound insulation theory of multilayered RCS

Transfer matrix of multilayered RCS is based on transfer matrix of monolayered RCS. For Equations (4), (5) and (6), coefficient matrices on the left can be marked by \( A_l \), and coefficient matrices on the right can be marked by \( B_l \). Thus, transfer matrix of multilayered RCS can be expressed as

\[
\begin{bmatrix}
P_{2i}/P_{nt} \\
P_{2r}/P_{nt}
\end{bmatrix} = \begin{bmatrix} \[0\] C^{(0)} \end{bmatrix} [ \begin{bmatrix} C^{(1)} \end{bmatrix} \cdots [ \begin{bmatrix} C^{(n-1)} \end{bmatrix} ] \]
\tag{11}
\]

where \( C^{(l)} = A_l^{-1}B_l \), \( l=0,1,\cdots,n-1 \).

Hence, sound pressure transmission coefficient \( t_p \) of multilayered RCS can be defined as

\[
t_p = \left| \frac{P_{nt}}{P_{is}} \right|
\tag{12}
\]

For complex multilayered RCS, such as RIWCCS or honeycomb sandwich RCS, distribution of sound energy in certain area is used to obtain STL without considering resonance among cavums. The distribution of sound energy is accorded with the area coverage in the same media. So STL of complex multilayered RCS can be defined as

\[
STL=20\log \frac{1}{t_p} = 20\log \frac{1}{t_{ps}} - 10\log \frac{1}{\Sigma (t_{ps}S/I_{S/D})}
\tag{13}
\]

where \( t_{ps} \) is sound pressure transmission coefficient in each medium (homogeneous material or air); \( S/I_{S/D} \) is the area percentage on cross section of each medium, it is a constant between 0 and 1.

### 3 NUMERICAL SIMULATION ANALYSIS

#### 3.1 Sound insulation performance of monolayered RCS

The influences of material property and panel’s thickness of rubber on sound insulation performance are discussed here. The thickness of steel plate is 10mm. The thickness ratio of rubber panel to steel plate is marked by \( d_1/d_2 \). The density of steel plate is 7700 kg/m\(^3\). Young’s modulus is 19.5×10\(^{10}\) Pa., Poisson’s ratio is 0.28. The density of water is 1026 kg/m\(^3\), and the sound speed in water is 1500 m/s.

The rubber layer is made of polyurethane as in literature [8]. Its density is 1100 kg/m\(^3\), and its Poisson’s ratio is 0.49. Its Young’s modulus and corresponding loss factor properties, which depend upon frequency and temperature, are given in Table 1. The temperature is 20 °C.

#### 3.1.1 The influence of adding rubber panel on structure sound insulation

The relations of Young’s modulus \( E \) (in 10\(^8\) Pa) and loss factor \( \eta \) with frequency (in kHz) and the temperature (in °C) for the polyurethane are shown in Table 1.

Fig.2 shows that STL of steel plate is small, while STL enhances visibly when steel plate with added rubber layer. Compared with low frequency range, STL increases evidently in middle and high frequency ranges. Numerical calculation shows that average STL increases by 3dB, while SSSL in high frequency range
increases by about 5dB after adding rubber panel. Fig.2 also shows that STL of monolayered RCS enhances with the increasing of frequency.

3.1.2 The influence of rubber layer thickness on STL

Fig.3 displays the influence on STL of monolayered RCS with rubber layers of different thickness. It can be seen that STL of monolayered RCS increases with the thickness of rubber. The thicker the polyurethane is, the better sound insulation performance of monolayered RCS is.

3.1.3 The influence of rubber material properties on STL

Rubber 1 is the material that mentioned in Table 1. The density of rubber is constant, and Young’s modulus, loss factor and Poisson’s ratio are changeable. Young’s modulus of rubber 2 is triple that of rubber 1, while its loss factor and Poisson’s ratio are constant. Young’s modulus of rubber 3 is one third of rubber 1, but its loss factor and Poisson’s ratio are unchanged, too. Loss factor of rubber 4 is triple of that of rubber 1, but Young’s modulus and Poisson’s ratio of rubber 3 are unchanged. Loss factor of rubber 5 is one third of rubber 1, but Young’s modulus and Poisson ratio are unchanged, too. Young’s modulus and loss factor of rubber 6 and rubber 7 are the same as those of rubber 1, but Poisson’s ratio of rubber 6 changes to 0.39 and Poisson’s ratio of rubber 7 changes to 0.44.

3.1.3.1 The influence of Young’s modulus on STL

Fig.4 shows that Young’s modulus of rubber has an obvious effect on STL of monolayered RCS. The reason is that modulus of soft rubber is small, so impedance difference is large between soft rubber and steel and which can reflect more sound energy into soft rubber and be absorbed by damping of soft rubber.

3.1.3.2 The influence of loss factor on STL
Fig. 5 shows that loss factor of rubber also has a visible influence on STL of mono-layered RCS. The larger loss factor of rubber is, the better sound insulation property of monolayered RCS is. The reason is that when loss factor of rubber is larger, energy in rubber is of more consumption, which is more advantageous for sound insulation of the structure.  

3.1.3.3 Influence on STL by Poisson’s ratio 

Fig. 6 shows that Poisson’s ratio of rubber material has a considerable influence on STL of monolayered RCS. Poisson’s ratio considered here is of positive value. The larger Poisson’s ratio is, the larger sound velocity in rubber and the larger rubber impedance are. In this way, impedance difference between rubber material and steel is smaller, which can transmit more sound energy to water and lead to worse STL of monolayered RCS. In other words, the smaller Poisson’s ratio is, the better STL of mono-layered RCS is.

As analyzed above, the properties of rubber material have an indirect influence on impedance matching degree between rubber, steel and water. As a result, they can effect sound insulation property of the whole structure.

3.2 Sound insulation performance of multilayered RCS 

Multilayered RCS is gained by adding more rubber layers on the basis of monolayered RCS, so rubber layers of multilayered RCS can be divided into outside rubber layers and inside rubber layers. In order to analyze conveniently, rubber 1 is used as outside rubber layer and the other rubber is used as inside rubber layers.

3.2.1 Sound insulation performance of multilayered homogeneous RCS 

The rubber layers are all homogeneous in multilayered RCS. Sound insulation performances of double-layered homogeneous RCS and triple-layered homogeneous RCS are investigated.

3.2.1.1 Sound insulation performance of double-layered homogeneous RCS 

In this section, rubber 1 and rubber 3 are adopted to form a double-layered homogeneous RCS. The thickness of the double-layered homogeneous RCS above equals to the thickness of monolayered RCS. The thickness ratio of two rubber layers to steel plate is 3:3:2, respectively. Fig 7 compares sound insulation performance of double-layered homogeneous RCS.
with that of two kinds of mono-layered RCS.

It is shown that STL of double-layered homogeneous RCS is close to the larger STL of mono-layered RCS in above two kinds, and sound insulation trend of double-layered homogeneous RCS is similar to that of mono-layered RCS.

3.2.1.2 Sound insulation performance of triple-layered homogeneous RCS

A layer of rubber 1 is added to double-layered homogeneous RCS to form a triple-layered homogeneous RCS, which is steel plate adding rubber 1 plus rubber 3 and rubber 1. The thickness ratio of rubber 1, rubber 3, rubber 1 and steel plate is 3:3:3:2. The thickness of triple-layered homogeneous RCS is larger than that of double-layered homogeneous RCS. Sound insulation comparison of triple-layered homogeneous RCS and double-layered homogeneous RCS are shown in Fig.8.

Fig.8 shows that sound insulation performance of triple-layered homogeneous RCS is better than that of double-layered homogeneous RCS in medium and low frequency range, especially in low frequency range. But in high frequency range, sound insulation performance of triple-layered homogeneous RCS is lower than that of double-layered homogeneous RCS, which depends on the property of rubber 1. So the other rubber materials can be considered to make STL be improved in high frequency range.

3.2.2 Sound insulation performance of RIWCCS

RIWCCS is gained by perforation inside rubbers of double-layered homogeneous RCS and triple-layered homogeneous RCS referred in 2.2.1.

3.2.2.1 Sound insulation performance of double-layered RIWCCS

The perforation is made equably inside rubber 3 in double-layered homogeneous RCS, and the perforation ratio is 0.45. Its sound insulation performance compared to non-perforation is shown in Fig.9.

By means of perforating equably inside rubber layer, it is shown that average STL increases by 2.5dB in Fig.9. So it is advantageous to improve sound insulation of the whole structure by the means mentioned above. There are two reasons, one is that the introduction of air can prick up impedance difference among materials and reflect more sound energy, the other is that the introduction of air can also form resonance among cavities to waste sound energy.

Fig.10 shows STL of double-layered RIWCCS becomes larger with the increase of perforation ratio of inside rubber layer, which further validates that there are advantages to improve STL of the whole structure through replacing homogeneous rubber by air.

3.2.2.2 Sound insulation performance of triple-layered RIWCCS

The perforation is made equably on inter-layer rubber (rubber 3) in triple-layered homogeneous RCS referred above to form triple-layered RIWCCS, which is also made by adding a layer of rubber 1 as bottom rubber on double-layered RIWCCS referred in chapter 3.2.2.1. The perforation ratio of triple-layered RI-
Numerical analysis and experimental study of sound insulation performance of underwater visco-elastic coated honeycomb surface panel - honeycomb core and rubber 3 with cavities. The perforation ratio is 0.35. Steel plate with added rubber 1 plus rubber 3 (rubber 1 and rubber 3). Sound insulation curve trends in frequency range depends on the material property of rubber 1, which is the same reason explained in chapter 3.2.1.2.

Furthermore, sound insulation curve trends are similar before and after perforation equally on inside rubber layer both in double-layered RCS and in triple-layered RCS. This shows that perforation can improve sound insulation performance of the structure in total, but not change sound insulation trend.

### 3.2.3 Sound insulation performance of honeycomb sandwich RCS

Honeycomb sandwich RCS is a special multilayered RCS. It can be widely used in the field of aviation, spaceflight and architecture, as in literatures [9, 10]. This paper puts forward a kind of honeycomb sandwich rubber structure on the basis of honeycomb truss structure, and brings it into underwater noise control field and discusses its sound insulation performance in condition of normal incidence.

#### 3.2.3.1 The model of honeycomb sandwich RCS

Honeycomb sandwich rubber structure in the paper is the structure of honeycomb between two rubber layers. A whole honeycomb includes surface panel, honeycomb core and bottom panel. In this way, honeycomb sandwich rubber structure is made up of outside rubber layer, honeycomb surface panel, honeycomb core, honeycomb bottom panel and bottom rubber layer. So it is a five-layer structure. Honeycomb sandwich RCS is to add honeycomb sandwich rubber structure onto steel plate, which is a compound sound insulation structure composed by six layers. Fig.12 shows the model of honeycomb sandwich RCS.

![Fig.10 The influence on sound insulation performance of double-layered RIWCCS by different perforation ratio. ( - the perforation ratio is 0.35, - the perforation ratio is 0.45, - the perforation ratio is 0.55).](image)

![Fig.11 Sound insulation performance of triple-layered RIWCCS compared to those of double-layered RIWCCS and triple-layered homogeneous RCS. ( - steel plate with added rubber 1 and rubber 3 with cavities, - steel plate with added rubber 1 plus rubber 3 and rubber 1, - steel plate with added rubber 1 plus rubber 3 with cavities and rubber 1).](image)

![Fig.12 The model of honeycomb sandwich RCS. (1-outside rubber layer, 2-honeycomb surface panel, 3-honeycomb core, 4-honeycomb bottom panel, 5-bottom rubber layer, 6-steel plate).](image)
Table 2 The parameters and dimensions of materials in honeycomb sandwich RCS.

<table>
<thead>
<tr>
<th>Number of layers</th>
<th>Material</th>
<th>$c/(\text{m/s})$</th>
<th>$\rho/(\text{kg/m}^3)$</th>
<th>$\sigma$</th>
<th>$E/\text{Pa}$</th>
<th>$\eta$</th>
<th>$d_i/\text{mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rubber 1</td>
<td>1100</td>
<td>0.49</td>
<td>changing</td>
<td>$7.1\times10^{10}$</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>aluminum</td>
<td>2700</td>
<td>-</td>
<td>7.1*10^10</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>air</td>
<td>343</td>
<td>1.21</td>
<td>343</td>
<td>-</td>
<td>-</td>
<td>4.5</td>
</tr>
<tr>
<td>4</td>
<td>aluminum</td>
<td>2700</td>
<td>-</td>
<td>7.1*10^10</td>
<td>-</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>rubber 1</td>
<td>1100</td>
<td>0.49</td>
<td>changing</td>
<td>$19.5\times10^{10}$</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>steel</td>
<td>7700</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>water</td>
<td>1500</td>
<td>1026</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

$\sigma$-Poisson’s ratio, $E$-Young’s modulus, $\eta$-loss factor, $d_i$-the thickness each layer and steel plate. The material of honeycomb is aluminium, honeycomb core is hexagonal topology, the thickness of honeycomb cell’s wall is 0.03mm, and the distance between two subtenses of honeycomb cell is 3mm.

Sound insulation performance of honeycomb sandwich RCS, in which outside rubber and bottom rubber are both rubber 1, which is simulated by adopting the parameters and dimensions in Table 2 and is compared with those of following two structures. One is replacing honeycomb in honeycomb sandwich RCS by rubber 1 of the same thickness with perforation ratio 0.45, which is rubber 1, rubber 1 with cavities, rubber 1 plus steel plate and the thickness ratio is 1:0.6:1:1. The other is to replace honeycomb by homogeneous rubber 1 of the same thickness without perforation, which is rubber 1 plus steel plate and the thickness ratio is 2.6:1. Fig. 13 shows STL of the three structures above in condition of normal incidence.

Sound insulation performance of honeycomb sandwich RCS is much better than those of other two structures in total is shown in Fig.13. The perforation on inside rubber can also improve sound insulation performance, but this can only improve sound insulation performance limitedly or locally. Hence, honeycomb sandwich RCS can produce more reflection and refraction and transform some longitudinal wave into transverse wave because of complex inner topology, so it can get much better STL.

4 EXPERIMENTAL RESULTS

The purpose of this section is to investigate the insulation characteristic of underwater honeycomb sandwich RCS by large sample free field method in anechoic pool of 20m×7m×8m. Its bottom and side walls are covered with
sound-absorption taper which can absorb the sound wave to ensure the least sound reflection. Fig.14 displays the experimental measurements setup.

The experimental model, whose area is 1m x 1m and the honeycomb structural parameters can be seen in Table 2. The experimental model was placed in the center of the pool and make sure that the geometry center is in the middle at 4m depth to reduce the reflection of the side wall and water surface as possible. Though the sound-absorption taper doesn’t have ideal effect at lower frequencies, its absorption coefficient between 20Hz~6kHz can be up to 0.8. So the sound reflection effect in this frequency range can be neglected. The model can be considered as being laid in infinite water. So the following only compares and analyzes experimental data and theoretical calculations above 500Hz.

According to the experimental purposes, the model in full frequencies from 500 Hz to 20kHz is excited. And the 1/3 oct is adopted to carry out the frequency analysis. Fig.14 displays STL of experimental data and theoretical calculations comparison diagram.

From Fig.15, we can conclude that the experimental data match theoretical calculations well. Fig.15 also displays that there are some differences between experimental data and theoretical results, which is that cavity resonance is omitted in theoretical model for simplifying analysis. Therefore, viscoelastic material has extra impact on STL, which directly influence the sound insulation characteristic of theoretical results.

5 CONCLUSIONS

In this paper, in condition of normal incidence, TMM is used to analyze sound insulation performance of monolayered RCS and multilayered RCS. For monolayered RCS, the influence on sound insulation performance by rubber material properties and the thickness of rubber panel is mainly investigated. For multilayered RCS, the advantages of multilayered RCS compared with monolayered RCS are mainly studied. The sound insulation effect before and after perforation equably on inside rubber is also discussed. In addition, sound insulation performance of honeycomb sandwich RCS is researched by theory and experiment, respectively. The following results can be achieved by the above investigations.

(1) The properties of rubber material have a large influence on SSTL of the structure. Rubber with small Young’s modulus and small Poisson’s ratio is adopted as outside rubber in order to improve STL obviously. STL of RCS develops with the increasing of rubber thickness, but there is huge localization on increasing SSTL of RCS at the cost of increasing the thickness of rubber.

(2) Multilayered RCS can combine advantages of according monolayered RCS, and achieve better sound insulation effect. It is of advantageous improving sound insulation performance by perforation on inside rubber. The larger perforation ratio of inside rubber is, the better sound insulation performance is.

(3) Because of complex inner topology, in condition of the same thickness, sound insulation performance of honeycomb sandwich RCS is much better than those of RIWCCS and homogeneous RCS.

(4) Results were consistent with measurement and theoretical prediction.

6 ACKNOWLEDGMENTS

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Abstract:
Based on the theory of wave transmission in infinite layered media, the authors have conducted theoretical and experimental studies on the acoustic properties of composite structure. Simulation results indicate that the properties of rubber materials have a significant impact on the acoustic performance. Soft rubber with low Poisson's ratio can greatly enhance the acoustic performance of the structure. Multilayered rubber structures exhibit superior acoustic performance compared to single-layered structures. Drilling holes in the rubber layers can effectively improve the acoustic performance. The more cavities there are, the better the acoustic performance. Honeycomb sandwich structures exhibit better acoustic performance compared to structures with cylindrical air cavities and multilayered uniform structures. Combining existing experimental conditions, a large-scale test of the honeycomb sandwich structure was conducted in anechoic chambers. The experimental data shows good consistency with the theoretical predictions.

Keywords:
Viscoelastic materials; Acoustic; Composite structure; Honeycomb sandwich; Free-field test; Anechoic chamber.

References: