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Measurement of reflection coefficient for a double-layered scaled model using the inverse filter

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Abstract. A method of measuring the reflection coefficient for a double-layered scaled model using the inverse filter is presented. First, the response of the circuit and underwater acoustical channel is measured, and the retransmitted inverse signal isestimated with the least square method for solving the cost function,which is constructed by the inverse filtering theory. Then, by retransmitting the inverse signal, the incident signal at the position of the double-layered scaled model is focused with high-main-lobe resolution, low side-lobelevel and a narrow pulse signal in temporal domain. The focus improves the measurement accuracy of the reflection coefficient for the double-layered scaled model in low frequencies. The feasibility of replacing the whole cylindrical with the double-layered scaled model is verified by simulation. The validity of the proposed method is verified by experiments carried out in a cylindrical tank for a double-layered scaled model at the frequency 0.5 kHz~10 kHz. The experimental results show that the proposed method is effective to the measurement of the reflection coefficient for the double-layered scaled model.The experimental results for the double-layered scaled model with acoustical coating on different shells have strongly directive significance for the process design and improvement of the acoustical coating.

1 Introductory

Acoustical coatingis quite important to a submarine for reducing the target strength against the detection of the active sonar. In order to evaluate the performance of the acoustical cladding layer effectively before equipping, it is necessary to take a certain part of the cabin model of submarine as the research object under the laboratory conditions, which is called double-layered scaled model. As an important intermediate link between the performance of the single sampleand the real application for the whole submarine, it is important to measure the performance of the acoustical coating effectively for the double-layered scaled model under the laboratory conditions.

The performance of the acoustical coating is characterized by reflection coefficient and transmission coefficient.(1) Actually, measurement of the reflection coefficient is more

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seriously affected by the test environment. Many methods were proposed in measuring the reflection coefficient, either for a small sample in sound tube or a large sample in free field environment.(2-12)Y. Z. Pan, X. P. Mo, *et al*. presented a wideband transducer for sound tube system, which satisfied the performance measurement for acoustic materials above 1.4 kHz to 23 kHz.(2)S. Li, *et al*. developed a travelling wave tube measurement technique and realized the acoustic properties measurement of underwater acoustic materials with frequency ranging from 100 Hz to 4000 Hz.(3)D. F. Ross and A. F. Seybert used a two-microphone random-excitation technique to determine the normal acoustic properties in a tube and an excellent agreement between the measuring values and the theoretical values was obtained.(4)H. Utsuno*et al*. realized the measurement of the characteristic impedance and propagation constant of porous materials using transfer function method, which obtained a reliable results and applied equally to characterizing the performance of underwater acoustic material.(5) The lower cost, better repeatability and more convenient procedure of the measurement for small samples in a tube make it extensive used in measuring the acoustic performance of acoustical coating. However, the measurement cannot reflect the real performance of the coating when it is equipped on the submarine with complex structure. The measurement methods for large samples in free field or a limited space environment overcome most of the drawbacks of that for a small sample in sound tube.(6-12)U. Ingård and R. H Boltpresented a free field method of measuring the absorption coefficient of acoustic materialsfor large samples and the experimental values were good agreement with calculations, but the effect of reverberation at low frequencies was inevitable.(6)M. Minten*et al*. applied the two-microphone technique to characterizing the absorption coefficient for large samples in an anechoic room and obtained reliable results with a harsh condition of anechoic performance of the room.(7)J. C. Davies*et al*. applied impulse method to measuring the normal impedance for large samples and the reverberation was decreased, but the spatial resolution couldn't be guaranteed due to the single channel projection.(8)M. Tamura*et al*. realized the accurate measurement of reflection coefficient for a large sample using spatial Fourier transform method, but the data analysis method was too complicated.(9,10)X. W. Yan*et al*. obtained a relatively accurate results of the acoustic performance for a large sample in a limited space using time reversal (TR) method, but the effect of the channel response couldn't be offset thoroughly due to the TR theory.(11) In addition, the measurement accuracy of the existing methods is decreasing with the frequency and the direct signal cannot be distinguished easily, especially for a double-layered scaled model, due to the influence of the multipath in a limited space environment and the double layers. What's more, the width of the main lobe is widening as the frequency decreasing, and once the main-lobe width is wider than the sample's size, the influence of the diffraction cannot be neglected. The multichannel inverse filter method (MIF) degraded the side lobe, enhanced the resolution of the main lobe and realized the optimal focusingby utilizing the coherent information of the different transmitting-receiving channel,(12)but the more complicated procedures were necessary, and the focusing effect was influenced by the number of transmitted transducers and the receivers, i.e. a high requirement of the hardware was necessary.

This paper presents a method for measuring the reflection coefficient of the double-layered scaled model using the inverse-filter transmission (IFT), which is distinguished with the method given by Ref. (12) by different objective functions. To construct the inverse filter, the response of the circuit and the underwater acoustical channel is estimated at first, and the retransmitted inverse signal can be estimated with the least square method for solving the cost function constructed by the inverse filtering theory. Then by retransmitting the inverse signal, the incident signal at the position of the double-layered scaled model is focused with a high-resolution main lobe, low level of side lobes and a narrow pulse signal in temporal domain. The reverberation is offset drastically, and the spatio-temporal focusing at the incident point can improve the measurement accuracy for a double-layered scaled model, especially for measurements at low frequency.

2 IFT Method and the Double-layered ScaledModel

2.1 Principle of the IFT method

The inverse-filter method has been widely used in various fields, more details of which are explained in Refs. (13-19), and here it is applied in underwater acoustical measurements, to be more precise, to measuring the reflection coefficient for a double-layered scaled model. The principle is briefly introduced to make this paper self-contained. The schematic of the whole measurement processes for inverse-filter transmission (IFT), including the estimation of Green's function (GF, i.e. the expression of the channel response in frequency domain) between the signal generator and the recorder, the construction of inverse filter, the generation of inverse signal, and its acquisition after transfer through the underwater acoustic channel and circuit channel, are shown in Fig. 1. The temporal probe signal (PS), formulated as the delta pulse regime and expressed as $x(t)$, is transmitted firstly by signal generator and received at the hydrophone. The receipt signal $y(t)$ as well as $x(t)$ are used to estimate the channel response using least square by minimizing the objective function. The more detail derivation of the inverse filter method is shown in Ref. (18), which is out of the scope of this paper. The main idea of this paper is how to use the IFT to realize the special-temporal focusing and the separating of the direct signal and the multiple reflections of the double-layer-scaled-model layers, and finally evaluating the reflection coefficient for a double-layered scaled model with more implementable procedures than that proposed in Ref. (12).

2.2 The double-layered scaled model

As one of the most deterrent underwater weapons, the concealment of submarine is the decisive factor of its combat effectiveness. There is no analytical solution for the scatter of the submarine due to its irregular shell structure, and the arithmetic solution can be obtained by using the finite element method.(20,21) However, the computational complexity is increasing in exponent when the volume of the structure is expanding. Meanwhile, the real acoustical performance of the acoustical coating is usually evaluated by lots of experiments before equipping. Nevertheless, the experiments carried out with a real model of the submarine are high cost and has poor repeatability. On those accounts, the double-layered scaled model is a better choice to satisfy a lower computational complexity compared with the real submarine cabin and the double-layered scaled model can reflect the real target strength of the real submarine cabin, and the experiments carried out with which in laboratory have a better repeatability, a much lower cost and a much higher efficiency.

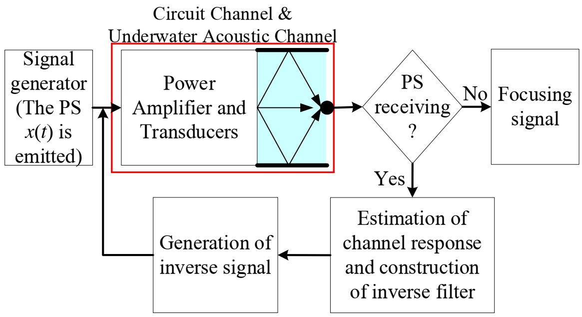

Fig. 1. (Color online) Schematic of the process for the inverse-filter transmission.

The submarine cabin is simplified with a cylindrical shell, which is 20 m in length, 8.6 m in diameter for the external shell with 8 mm in thickness, 7 m in diameter for the internal shell with 30 mm in thickness, and 8 mm in thickness for the ribbed structure.The cylindrical shell andthe double-layered scaled model of the cylindrical shell,are shown in Figs. 2(a)-(b). Fig. 2(c) shows the comparison, simulated by Hyper Mesh software,between the target strength change for the whole cylindrical shell and the double-layered scaled model covered with a certain type of acoustical coating on the external shell or not. From Fig. 2(c), it is obvious that the double-layered scaled model can reflect the real target-strength-change properties of the whole cylindrical shell when it was equipped with acoustical coating or not.What's more, it can also be interpreted that the acoustical coating is efficient to decrease the target strength for the double-layered scaled model and for the whole cylindrical shell meanwhile. A simulation was also done using Hyper Mesh software for the double-layered scaled model with a type of acoustical coating covered on the external shell.The target strength, shown in Fig. 2(d),was compared with the result obtained by the samedouble-layered scaled model when there was no acoustical coating covered on it. Form Fig. 2(d), it is apparently that the target strength for a double-layered scaled model covered with acoustical coating is much lower than that without acoustical coating.

The acoustical coating covering on the internal or external shell has different performance for the double-layered scaled model.Because the shape of the double-layered scaled model is similar to the submarine and it was shown that its target strength curves are close to those of submarines(i.e. the whole cylindrical shell in this paper), so the results obtained from the double-layered scaled model, not only the simulations, but also the real experimental results, have strongly directive significance for the process design and improvement of the acoustical coating. To evaluate the reflection coefficient of the double-layered scaled model efficiently in laboratory when different acoustical coatings are equipped on it, the IFT method, which realizes the spatial-temporal focusing and separates thedifferent reflections of the shells from the direct signal, will be utilized. The procedures of the implementation of the IFT method, as well as the experimental results are given in the following(sub-) section.

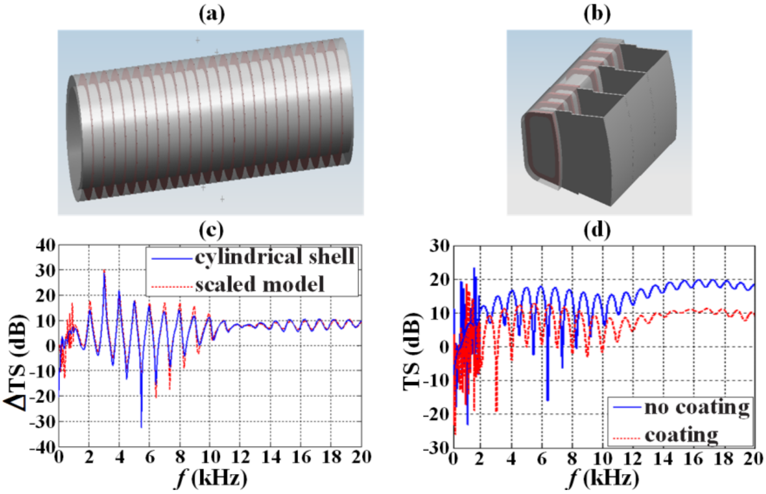

Fig. 2. (Color online)Simulation models of (a) the cylindrical shell and (b) the double-layered scaled model, (c) is the target strength change of the two models with coating or not, and (d) is the target strength for the double-layered scaled model with coating or not.

3 Results and discussion

3.1 Measurement system

The measurement system for the double-layered scaled model is illustrated in Fig. 3(a). In order to obtain the average reflection coefficient of the model, a five-element cross array, with 25 cm in the adjacent elements' spacing, is employed. And the whole system is composed of the signal generator, the power amplifier, the transmitted transducer array, the multichannel signal acquisition system and the filter amplifier.

It is well known that in a non-anechoic environment, at a given distance between the source and the receiver, the direct-to-reverberation ratio is related to the directivity factor of the transmitted transducer. (22) And in many cases, this indicator is not sufficient for a single transducer, so the MIF method proposed in Ref. (12) used three transducers to obtain a bigger direct-to-reverberation ratio but introduce some more complex procedures and higher requirements of the hard ware at the same time. In order to obtain a high direct-to-reverberation ratio, decrease the measuring complexity and satisfy the hardware requirement easily, a large aperture circular array, which has sharp directivity, is applied in the experiment when the IFT methodis used. The large aperture circular array is about 1 m in diameter and consists of 127 elements.

The performance of underwater acoustical coating is usually measured in a limited space under the laboratory conditions, and it is in a semi-anechoic cylindrical tank in this paper, To reflect the real performance of the acoustical coatingbefore equipping on submarines, the acoustical coating is laid on the double-layered scaled model, shown in Fig. 3(b), to characterize the acoustic performance. The measurement procedures using these instruments, as well as the results, are described in the following (sub-) sections in detail.

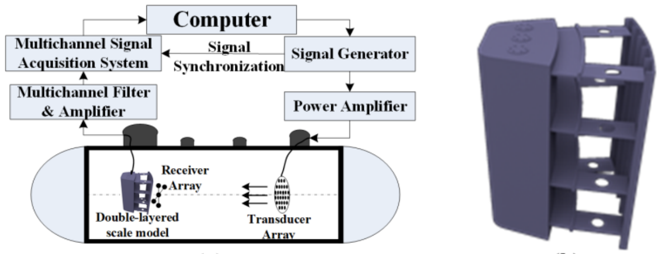

Fig. 3. (Color online) (a) Measurement system and (b) the material to be measured.

3.2 Experiments and data analysis

3.2.1 Measurement procedures

The whole processes of the signal from generator to receiver are described as follows. Firstly, the PS, generated by the signal generator and amplified by power amplifier, is transmitted by the transducer array and recorded by the multichannel signal acquisition system after being filtered and amplified. The channel response and the inverse-filter coefficients are estimated using the inverse-filter algorithm in computer, and the retransmitted signal is calculated using the original signal and the inverse-filter coefficients meanwhile.

For the whole procedures, firstly, the retransmitted signal is transmitted by the transducer array without the model suspended near the receiver array, and the focusing signal, denoted by $p_i(\omega)$, is recorded by the desired hydrophone. Then, the reflection signal, denoted by $p_r(\omega)$, is recorded at the same position when the model is placed in the field. Finally, the reflection coefficient was calculated by[1]

$$r_p(\omega) = \frac{p_r(\omega)}{p_i(\omega)}, \tag{1}$$

and the average reflection coefficient can be calculated with five times focusing measurement results.

3.2.2 Experimental data processing

In order to verify the focusing effect in spatio-temporal domain when the IFT method is used in experiments, some experiments and data processing results are given in this subsection.

As the procedures described in the prior subsection, the measurement process begins with an emission of PS formulated as the delta pulse regime. Herein, the experiments, whenthere was no model in the acoustical field, were carried out in the cylindrical tank, which wascovered by sound absorbing materials whose absorption coefficient is higher than 95% above 3 kHz in frequency.The tank was 25 m in length, 4 m in diameter and the two ends were anechoic. The receiver array was placed on the axie wire with a distance of 4.5 m from the transmitted transducer array. The results are shown in Fig. 4, where (a) is the temporal signal, i.e. the channel response obtained using broadside transmission (BST), received by the hydrophone, which is obviously influenced by the performance of the hardware and the multi-path interference produced by the tank's boundary, (b) is the temporal signal reconstructed after applying the inverse-filter coefficient to the channel response with numerical calculation. (c) and (d) are the corresponding frequency response levels of (a) and (b), respectively. From Fig.4, compared with BST, some obviously improvements for the temporal-waveform focusing and the frequency response level have been obtained using the IFT method. In other word, if the original signal, expressed as $q(t)$, is processed with the inverse-filter coefficient, the multi-path interference will be offset, and a perfect focusing signal in temporal-frequency domain will be obtained.

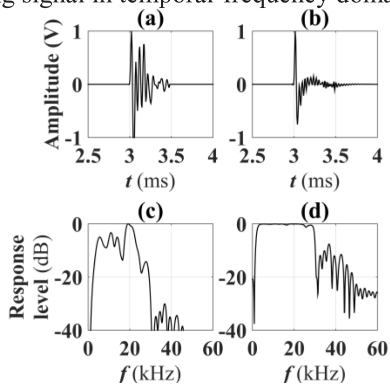

Fig. 4. Responses in temporal-frequency domain obtained via BST and the IFT method. (a) and (b) are the response obtained via BST, (c) and (d) are the corresponding frequency response levels of (a) and (b).

In consideration of the practical available bandwidth of the hardware (especially the transmitted transducer), the original signal is defined as the second derivative of a Guassian-type explosive signal,(23) formulated as

$$f(t)=\begin{cases}-2A\pi^2 f_0^2\left[1-2\pi^2 f_0^2\left(t-t_0\right)^2\right]e^{-\pi^2 f_0^2 (t-t_0)^2}, 0<t<2t_0\\ 0,\ \text{otherwise}\end{cases}, \tag{2}$$

where$A$ isthe amplitude modulation coefficient, f_0 is the central frequency, $t_0 = 1/f_0$. Herein, in order to match with the performance of the hardware, the parameters are chosen as $A=1,\ f_0 = 5\ \text{kHz}$. The performance for the spatial-energy focusing and the temporal-waveform focusing of the proposed method is validated by an experiment carried out using $f(t)$, and the results are illustrated in Fig. 5, where Fig. 5(a) and Fig. 5(b) are the temporal signalreceived by the central hydrophone of the five-element cross array and the spatial-energy distributions via BST, (c) and (d) are the corresponding results via IFT, in which the focusing position is selected at the central hydrophone. Form Fig. 5, it is quite clear that the spatial-energy distribution via BST is scattered in all of the elements while the energy is focused on the right hydrophone (i.e. the central element of the array, which is indicated with a cross sign) via IFT, the amplitude of direct signal in Fig.5(a) via BST is less than that via IFT in Fig. 5(c), which is focused with lower reverberation, and the reverberation shown in (a) might make it difficult to extract the direct signal and the multiple reflection signals to evaluate r_p accurately.

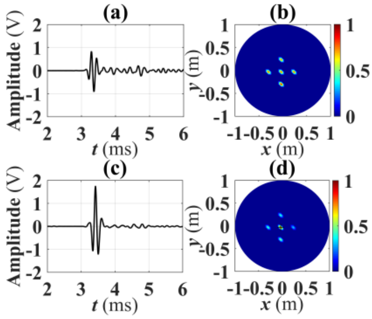

Fig. 5. (Color online) Comparisons of performance for the spatial-temporal focusing via BST and the IFT method. (a) and (b) are the temporal signal received by the central hydrophone of the five-element cross array and the spatial-energy distributions via BST, (c) and (d) are the corresponding results via IFT.

3.2.3 Measurementresults for double-layered scaled model without coating

To demonstrate the validity of the IFT method in acoustical measurement, experiments for a double-layered scaled model were carried out in the cylindrical tank. The geometricalshape of the model is illustrated in Fig. 6, where Fig. 6(a) is the double-layered scaled model and Fig. 6(b) is the simplified model for the calculation of theoretical values(1).

The experiment for measuring the reflection coefficient was performed with the signal expressed as $f(t)$ in Eq. (2) and $f_0 = 5\ \text{kHz}$. The measurement values were calculated by averaging the five values evaluated via sampling data from the five hydrophones, independentlyfocusing on the hydrophone positions based on the procedures described in subsection 3.2.1. The receipt focusing signal of the central element in the five-element cross array for the double- layered scaled model,as well as the reflection coefficients evaluated in frequency domain for this model, and the theoretical results in the free field, are illustrated in Fig. 7. From Fig. 7(a), the direct signal is separated from the outer- and inner-shell reflections for the double-layered scaled model in temporal domain, and from (b), the reflection coefficients evaluated via IFT are in a certain good agree with the theoretical values for the double-layered scaled model. In addition, the error of the measurement results in medium-high frequency in Fig. 7(b) is a little larger than that in low frequency, which is because the reflection coefficient of the outer shell is increasing and the transmission coefficient is decreasing in medium-high frequency, so the transmission lose resulting from the repeated reflections between the inner and the outer shell is higher than that in low frequency, and finally leading to the higher error in medium-high frequency. What's more, the theoretical values are calculated by the simplified model and the real model has more complicated structures such as the ribbed plates, which is one of the main reasons resulting in the measuring error.

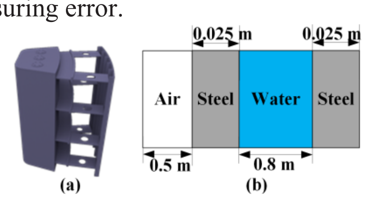

Fig. 6. (Color online) The geometry of the double-layered scaled model. (a) is the real model and (b) is the simplified model for the calculation of theoretical values.

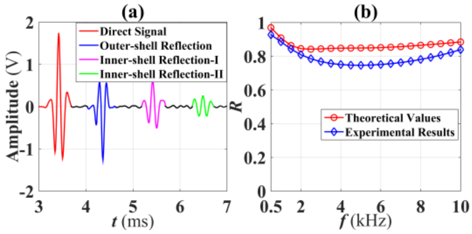

Fig. 7. (Color online) Focusing signals and the measurement and theoretical results for a double-layered scaled model. (a) is the focusing signal for a double-layered scaled model, (b) are the measurement and theoretical results for the model using the IFT.

3.2.4 Measurementresults for double-layered scaled model with coating

The acoustical coating will show different performance in different intensity of pressure. And a different target strength of the double-layered scaled model will be displayed when the acoustical coating are equipped on different shells, which can reflect the real target strength of the submarine cabin when the same acoustical coating is applied.

The effect of the IFT method for the reflection coefficient of the double-layered scaled modelhas been verified in subsection 3.2.3, and using the similar deployment, the similar procedures and the similar signal processing method, some experiments were carried out for double-layered scaled model with coating on different shells. Fig.8(a) shows the measurement results of the reflection coefficient when a certain type acoustical coating was equipped on the external shell of the double-layered scaled model under some intensity of pressures including 0.1 MPa, 0.5 Mpa, 1.0 MPa, 1.5 Mpa and 2.0 MPa. The measurement results of the reflection coefficient when a certain type of acoustical coating was equipped on the internal shell under the same measuring condition are shown in Fig. 8(b), and the acoustical coating was equipped on the internal shell and the external shell at the same time, the different measurement results of the reflection coefficient were calculated, which are illustrated in Fig. 8(c).From Fig. 8(a), it is obvious that the acoustical coating equipped on the external shell decreased the reflection coefficients of the double-layered scaled model in all of the intensity of pressure comparing with the results shown in Fig. 7(b). When the coating was equipped on the internal shell, the reflection coefficients of the double-layered scaled model were increasing with frequency for all of the intensity of pressure, the reason of which was the main reflection come from the external shell, and the signal transmitted through the external shell to the internal shell was attenuating by the external shell, especially at high frequency. Although most of the signal could transmitted through the external shell (with no acoustical coating) in low frequency and the reflection coefficient was small, the acoustical coating equipping on the internal shell attenuated most of the transmitted signal of the external shell, leading to a smaller reflection signal. So the reflection coefficients at high frequency are higher than that at low frequency, which are shown in Fig. 8(b), but the effect of the acoustical coating is still obvious comparing with Fig. 7(b). And when the external shell and the internal shell were all equipped with acoustical coatings, some much smallerreflection coefficients, shown in Fig. 8(c), were obtained in all of the intensity of pressure. What to be pointed out is that the reflection coefficients of the double-layered scaled model with acoustical coatings differ from the intensity of pressure, which is because the performance of the coating is different in different intensity of pressure. The acoustical coatings mentioned above are not the same type. The measurement results of the reflection coefficient for the acoustical coating equipping on the double-layered scaled model have strongly directive significance for the process design and improvement of the acoustical coating.

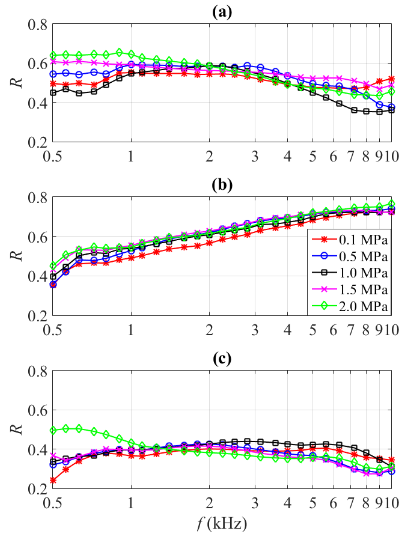

Fig. 8. The measurement results of the reflection coefficient for the double-layered scaled model with acoustical coating on (a) the external shell, (b) the internal shell and (c) the ex- and the internal shells.

4 Conclusion

The measurement of reflection coefficient for a double-layered scaled model in a limited space using the inverse filter was presented. Because the shape of the double-layered scaled model is similar to the submarine and it was shown that its target strength and target strength change are all closer to those of submarinesthan conventionalflat plate, the results of the measurement in the cylindrical tank can better reflect the performance of the acoustical coating in practice. The measured reflection coefficients for the double-layered scaled modelwithout acoustical coating agree wellin most frequencies with the theoretical values calculated in free field.And the measured reflection coefficients for the double-layered scaled modelwith acoustical coating are different from the laid shells and the intensity of pressure, which can be a significant reference to the process design and improvement of the acoustical coating. It should be pointed that the main limitation of the IFT method is the measurement environment during the measuring procedures must be kept unchanged to ensure the relative invariance of the channel response. What's more, the performance of the hardware will influence the accuracy of the measurement results.

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