Journal of Sound and Vibration 426 (2018) 54–74

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Influence of hole shape on sound absorption of underwater anechoic layers

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A R T I C L E I N F O

Article history:
Received 8 June 2017
Received in revised form 6 April 2018
Accepted 6 April 2018
Available online 24 April 2018
Handling Editor: R.E. Musafir

Keywords:
Underwater anechoic layer
Sound absorption
Hole shape
Analytical modeling

A B S T R A C T

A theoretical model is established to evaluate the sound absorption performance of underwater anechoic layers containing periodically distributed axial holes. Based on the concept for homogenized equivalent layer and on the theory of wave propagation in viscoelastic cylindrical tubes, the transfer function method is used to obtain the absorption coefficient of the anechoic layer adhered on the rigid plate. Three different types of axial holes are considered, the cylindrical, the conical and the horn shaped one. Results obtained with full finite element simulations are used to validate the model predictions. For each hole type, the vibration characteristics of the anechoic layer as well as the propagation of longitudinal and transverse waves in the layer are analyzed in detail to explore the physical mechanisms underlying its absorption performance. Furthermore, a three-dimensional finite element model for oblique incidence is developed to study the effect of hole shape at different incidence angles. The results show that two new absorption peaks appear since the oblique incidence excites two horizontal modes. Among the three hole types, the horn one achieves the best absorption performance at relatively low frequencies both in normal incidence and in oblique incidence.

1. Introduction

Underwater anechoic layer is vital for the acoustic stealth of submarines, which is usually made up of rubber coatings containing periodically distributed inner holes. Early in the 1950s, Blake [1], White [2] and Meyer et al. [3] investigated oscillations and wave propagation in solid media with inner holes. Gaunaurd [4] then established an one-dimensional (1D) model to analyze the eigenfrequency and acoustic absorption of a viscoelastic medium containing short cylindrical holes. Subsequently, Lane [5] and Gaunaurd [6] revealed two types of resonance mechanism for Alberich anechoic layers, i.e., radial motion of hole wall and drum-like oscillation of cover layer, and discussed their relative importance. While Jackins et al. [7] and Strifors et al. [8] studied the reflection of bilaminar structures, Jackins et al. [7] constructed the resonance scattering theory for the reflection of a bilaminar rubber containing spherical air-filled perforations of various concentrations in each layer. Taking the fluid-loaded coated elastic plate into consideration, Strifors et al. [8] analyzed the reflection of a bilaminar structure consisted of a viscoelastic coating and a coated elastic plate. It has been established that the method of transfer function is convenient for calculating the acoustic characteristics of multilayered structures. Cervenka et al. [9] deduced the

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https://doi.org/10.1016/j.jsv.2018.04.008

transfer matrix of a multilayered structure of which each layer can be either liquid or solid. Stepanishen et al. [10] and Liang et al. [11] studied the acoustic performance of a multilayered structure at oblique incidence, using the transfer function method. As to the anechoic layer with gradually varying axial holes, the concept of equivalent layering needs to be introduced. Tang et al. [12] proposed a two-dimension analytical model for axisymmetric wave propagating in cylindrical tubes, and concluded that only the first effective wave propagation mode needed to be considered at low frequencies. Further, by applying the transfer function method, Tao [13] studied such a kind of anechoic layers containing conical, sinusoidal or cosinoidal holes by layering the gradually varying axial holes into a cluster of cylindrical holes with different diameters so that each layer may be approximated as a cylindrical tube. .

Apart from theoretical analyses, finite element method (FEM) has been employed to study various kinds of anechoic layers. Hennion et al. [14] and Easwaran et al. [15] developed finite element (FE) models to calculate the acoustic properties of anechoic layer containing doubly periodic holes. Langlet et al. [16] further investigated the difference in resonance frequencies between plates without holes and those with holes, while Hennion et al. [17] constructed a FE model for anechoic layer containing grating of elastic tubes. Panigrahi et al. [18] investigated acoustic coatings with different sizes of air channel adhered on the same side or different sides of a steel wall. In addition to FEM, experimentally, Peng et al. [19] developed a modified method to measure the transmission coefficient of a multilayer acoustical panel in impedance tube. They improved the measuring precision and reduced the demand of the tube end.

Although acoustic coatings containing solid particles that may play the role of scattering [20] or local resonance have been proposed [21–24], such coatings are relatively heavy in comparison with those containing inner holes. It is therefore important to investigate the influence of hole shape on acoustic properties of coatings containing inner holes. Ivansson studied anechoic coatings with spherical [25] and superellipsoid [26] holes by adapting techniques used in electron scattering and band-gap computations for photonic and phononic crystals. Ivansson [27] compared anechoic coatings containing cylindrical holes having different cross-sectional shapes (circle, ellipse and superellipse) and used Markov-chain Monte Carlo method to obtain optimal solutions. Shang et al. [28] found that conical holes are superior to cylindrical holes for enhancing the sound absorption performance of anechoic layers. On the other hand, the backing effects [29–31] have been well investigated when the anechoic layer is attached with elastic plates in recent years. However, these works [29–31] still lack detailed analyses for the effect of different inner holes in anechoic layers. In this point, a lot of researches connected to heterogeneous foams for airborne sound [32–34] can provide interesting insights to the present underwater sound, especially for the works regarding with double porosity materials [35–37].

Rubber-based anechoic layers containing gradually varying axial holes are widely used as submarine acoustic coatings. Due to the close impedance between water and rubber as well as the gradually varying impedance of the anechoic layer along its thickness direction, an incident wave can easily propagate into the layer and then be gradually absorbed. Although existing researches [13,28] have examined how various hole shapes, such as cylindrical, conical and horn-like holes, affect the acoustic performance of anechoic layers, further research is needed to explore the profound absorption mechanism of the layer, quantify the absorption difference among various hole shapes, and provide exact equations describing the absorption curve of horn-like holes. To address these issues, the current study employs the transfer function method to establish a theoretical model for analyzing the sound absorption property of anechoic layers containing periodically distributed and gradually varying axial holes; the concept of equivalent layering as well as the existing theory of wave propagation in viscoelastic cylindrical tubes are also employed. For validation, the commercially available FE code COMSOL Multiphysics is used to obtain full numerical results and compare with theoretical model predictions. Three kinds of hole configurations are modeled: the cylindrical hole, the conical, and the horn shaped one, with the exponential function chosen to describe the generatrix of the horn hole. Special focus is placed upon the propagation of longitudinal and transverse waves in the anechoic layer and the effect of hole configuration on sound absorption. To address the oblique incidence case, a three-dimensional FE model is developed to analyze the influence of different hole shapes and different incidence angle on sound absorption performance of the underwater anechoic layer.

2. Theoretical model

In this section, we will develop a theoretical model by combining the two-dimensional simplification approach for axisymmetric wave propagating in cylindrical tube [12] and the layer-wise method for a anechoic layer with gradually varying axial holes [13]. In this model, the homogenization approach is used to calculate the effective acoustic impedance for each divided layer, and then the transfer matrix method is adopted to calculate the sound absorption coefficient.

Fig. 1 presents the configuration and working condition of a representative underwater anechoic layer (rubber) containing periodic inner holes that is adhered to a steel plate. The transverse size of the bi-layer structure is assumed to be infinite. The medium at one side of the structure is water while the medium at the other side is air, both taken as spatially semi-infinite. When an incident plane sound wave propagates from the far field in the water into the anechoic layer, the wave is attenuated. As the steel plate is supposed to be a rigid back, the wave completely reflects back and eventually into the water. For simplicity, only the case of sound waves normal incidence is considered in the theoretical model, while the case of sound wave oblique incidence will be handled by numerical simulations.

A typical arrangement of the periodical holes in the anechoic layer is shown in Fig. 2. In the axial (vertical) direction, the holes keep abreast with each other, while in the transverse (horizontal) direction they conform to regular triangular arrangement. Due to periodicity, only a single cell with hexagonal perimeter needs to be extracted for further study. However,