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Sound absorption of a new bionic multi-layer absorber

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ABSTRACT

The interest of this article lies in the proposition of using bionic method to develop a new sound absorber. Inspired by the coupling absorption structure of a typical silent flying bird–owl, a bionic multi-layer structure is developed, which is composed of micro-silt plate, porous fibrous material and flexible micro-perforated membrane backed with airspace. The impedance transfer method and finite element simulation method (ACTRAN) are applied to calculate the acoustic performance and analyze the influence of different parameters of each layer on absorption coefficients of this model. The effectiveness of this proposed model is tested based on numerical simulations. The average normal incidence absorption coefficient reaches 0.85 within the frequency range from 200 to 2000 Hz. The significant improvement of absorption coefficients can be mainly due to the Helmholtz effects of micro-silt plate and flexible micro-perforated membrane, and the combination with porous materials lead to even better absorption performance in broadband.

1. Introduction

In recent years, noise control has attracted much attention for improving living environments. Multi-layer acoustic absorbers composed of perforated plates, airspaces and porous materials are commonly applied to absorb broadband noise. However, the acoustic absorption of these multi-layer acoustic absorbers is mainly dependent on their fabrication. In this paper, a new absorption structure is developed through biomimetic method, and the factors that have significant influence on the acoustic absorption performance are analyzed.

Biology has perfected its designs and formed many fruitful abilities through evolution of billions of years. Efficient and reliable technologies and achievements can be developed by adopting the features of natural creations [1–5]. The owl, as observed today, has passed through series of evolution for over 12 million years. It is suggested that the owl has developed its strategy of a silent predator based on various characteristics of its body surface. At present, in the field of bionics, investigations on the noise reduction characteristics of owl body surface are mainly focused on its morphological features. Through comparative experiments on morphological characteristics of owl's wing surface, Graham [6] revealed that its special wing feathers had a significant impact on noise reduction capacity. Based on pneumatic noise test during the predation process of striped owl, Kroeger et al. [7] found that the primary feather edge was indented, which was conducive to noise suppression and even influenced its physical trajectory. Through long-term observation and experiments, Lilley [8] proposed following tentative but plausible reasons for the reduction and suppression of noise: (1) leading edge of primary feathers in the form of a comb, (2) trailing edge feathers in the form of a fringe, and (3) fluffy down on the wings, abdomen, legs and tarsus. On this basis, Lilley [9] attempted to optimize the take-off and landing of quiet commercial passenger transport according to the noise reduction characteristics of owl body surface and obtained satisfactory results. Ren et al. [10] and Liu et al. [11] in our group considered that the skin and feather of owl chest and abdominal may also play an important role on its silent flight. It was concluded that the noise suppression of the owl chest and abdominal was due to the synergy effect of material, skin structure and feather shape, etc., and further named as biological coupling. Inspired by this fact, a bionic coupling multi-layer structure is established in this article according to the bionic analogy principle.

The Smart Trim Technology Laboratory at the University of Delaware has developed an acoustic boundary control concept for active control to suppress interior sound radiation in helicopters, fixed-wing aircraft and land vehicles [12–15]. Hirsch et al. [16] presented the acoustic boundary control method and proposed a mathematical model of curved composite trim panels with impedance method. Davern [17] presented an experimental study on a three-layer assembly which contained perforated plate, porous

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material and airspace. Dunnand and Davern [18] proposed an analytical analysis for the flat-walled anechoic lining composed of outer, middle and inner layer porous materials. Jinkyo et al. [19] further studied the assembly with two layers of perforated plates backed with airspaces using equivalent electrical circuit method (EECM). Chen et al. [20] applied finite element method (FEM) to analyze the acoustic absorption of porous materials with different surface shapes and perforated plates. Buitrago et al. [21] gave a simulation analysis of Sandwich panels with carbon/epoxy skins and an aluminium honeycomb core by implement the model in ABAQUS/Explicit. Koutsawa et al. [22] presented a multi-scale model of viscoelastic constrained layer damping treatments for vibrating plates/beams and analyzed the sound transmission loss of the sandwich structure by the use of a sound transmission model. Wang et al. [23] presented a theoretical study on the sound transmission loss characteristics of unbounded orthotropic sandwich panels considering the transverse shear deformation. Larbi et al. [24] presented the theoretical formulation and the finite element implementation of vibroacoustic problems with piezoelectric composite structures connected to electric shunt circuits. Lin et al. [25] provided a detailed investigation of the impact of porous materials with different thickness and configuration on the perforated plate. Lee and Kwon [26] estimated the absorption performance of multiple layer perforated plate systems by transfer matrix method (TMM). Lee and Chen [27] proposed acoustic transmission analysis method to analyze the absorption of multi-layer absorber, which was subsequently developed into the impedance transfer method (ITM). Zhao et al. [28] compared EECM, ITM and TMM, and proved that ITM and TMM were essentially the same and more accurate than EECM. Recently, a variety of acoustic simulation software based on FEM are developed to be more convenient and visualized to investigate the various acoustic performance of absorption structure. Accordingly, ITM and FEM with ACTRAN are selected among all the methods for the acoustic analyses in this study.

2. Materials and methods

2.1. Establishment of the bionic model

Ren et al. [10] investigated the acoustic performance of the chest and abdominal skin and feather samples of long-eared owl, pheasant and pigeon. Some bionic characteristics of long-eared owl (a. ribbed structure of feather surface, b. micro-slit structure of feather, c. fibrous structure of fluff, d. cavity under the dermal layer of skin) and absorption comparison of different bird samples (e) are displayed in Fig. 1.

Fig. 1e indicates that the absorption coefficients of owl skin and overlying feathers are much higher than the other two birds, especially within the frequency range from 1000 Hz to 4000 Hz. In the present study, bionic coupling modeling method is used to analyze the surface noise reduction mechanism based on the absorption characteristics of long-eared owl. The bionic analogies are characterized as follows: (1) The covering feather is analogous to rigid micro-slit plate, (2) The chest fluff is analogous to uniform fiber absorption material, (3) The dermis layer and subcutaneous cavity are analogous to a sound absorber, which compose of flexible micro-perforated membrane and airspace. The bionic coupling structure (a) and some comparative models (b) are shown in Fig. 2. Fig. 2b is composed of model 1 (a micro-slit plate backed with airspace), model 2 (a micro-slit plate backed with porous material), model 3 (double layer structure of micro-slit plate and micro-perforated membrane), model 4 (multi-layer structure of micro-slit plate, porous material and airspace) and model 5 (multi-layer structure of micro-slit plate, porous material, micro-perforated membrane and airspace). The first four are contrast models and the fifth is the bionic model.

2.2. Calculation method of acoustic performance

The methods used to analyze the various absorption performances in the study are discussed in following sections.

2.2.1. Acoustic impedance of rigid micro-silt plate

The calculation of acoustic performance of micro-slit plate is based on Maa's micro-silt theory [29] and expresses in the following equations:

$$Z_p = \rho_0 c_0 (r + j\omega m) = \frac{12\eta t}{p\rho_0 c_0}\left(1+\frac{x^2}{18}\right)^{0.5} + \frac{j\omega t}{pc_0}[1+(25+2x^2)^{-0.5}] \quad (1)$$

$$Z_D = -j\rho_0 c_0 \cdot \cot\left(\frac{\omega D}{c_0}\right) \quad (2)$$

$$Z = Z_p + Z_D \quad (3)$$

where $\omega = 2\pi f$, f is the frequency, $x = 0.5d\sqrt{\omega/\mu}$ is the perforated constant, $j = \sqrt{-1}$, t, d, p are the thickness, width of micro-slit and porosity of micro-slit plate, respectively. η, ρ_0, c_0 are the kinematic viscosity of air, density of air and sound speed, D is the thickness of the airspace behind the micro-slit plate, Z_P, Z_D and Z are the impedances of micro-slit plate, airspace and micro-slit absorber.

In the case of oblique incidence, when a sound wave is incident at an angle θ to the normal, the relative acoustic impedance of the cavity with thickness of D becomes $\frac{1}{j\cos\theta}\cot\left(\frac{\omega D\cos\theta}{c_0}\right)$. If the incident direction of sound wave is vertical with the length direction of micro-slit, the normalized specific acoustic impedance is thus as Eq. (4). If it is parallel with the length direction of micro-slit, the normalized specific acoustic impedance is thus as Eq. (5):

$$Z_\theta = r\cos\theta + j\omega m\cos\theta - j\cot\left(\frac{\omega D\cos\theta}{c_0}\right) \quad (4)$$

$$Z_\theta = r + j\omega m - j\cot\left(\frac{\omega D\cos\theta}{c_0}\right) \quad (5)$$

2.2.2. Acoustic impedance of porous material

Considering the accuracy and simplicity, Delany–Bazley–Miki [30] model is proposed to evaluate the wavenumber k and characteristic impedance Z_c:

$$Z_c = \rho_0 c_0\left[1 + 5.50\left(10^3\frac{f}{\sigma}\right)^{-0.632} - j8.43\left(10^3\frac{f}{\sigma}\right)^{-0.632}\right] \quad (6)$$

$$k = \frac{\omega}{c_0}\left[1 + 7.81\left(10^3\frac{f}{\sigma}\right)^{-0.618} - j11.41\left(10^3\frac{f}{\sigma}\right)^{-0.618}\right] \quad (7)$$

$$\text{For } 0.01 < \frac{f}{\sigma} < 1.00 \quad (8)$$

where σ is the resistivity of porous material.

2.2.3. Acoustic impedance of micro-perforated membrane

A micro-perforated membrane backed by airspace makes a resonant system, which can be obtained using the impedance type of electro-acoustic analogy. Basically, the resonant system contains the mass-resistance element in series with the cavity reactance of the airspace [31]. The acoustic performance can be represented by the following equations: