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Acoustic behavior prediction for low-frequency sound quality based on finite element method and artificial neural network

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ABSTRACT

In this paper, a hybrid approach called FEM-ANN model is proposed by combining the finite element method (FEM) and artificial neural network (ANN) to predict the acoustic behavior of an auditory system. Based on the scanned point cloud data, the three-dimensional numerical models of the external auditory canal, tympanic membrane and middle ear are established by using the reverse prototyping technology, as are the FEM models. Setting the interior noises of the vehicle as excitations, the assembled FEM model is used to calculate the responses of the stapes footplate. According to the auditory perception characteristics of the human, a modified one-third octave filter bank is designed to calculate the vibration energies of stapes footplate in the critical bands, and thereby an energy-based feature matrix is established. Further, the sound quality (SQ) indices of interior noises, such as A-weighted sound pressure level (SPL), loudness and sharpness are calculated. By considering the extracted feature matrices as inputs and the calculated SQ indices as outputs, a three-layer ANN model with the radial basis function (RBF) is established for mapping the stapes footplate vibration to the human auditory perception. Verifications show that, the simulated result from the FEM model is consistent with that of the classical Ferris' model. The error percentages of A-weighted SPL, loudness and sharpness predicted by the FEM-ANN are all less than 5%, which suggests that the FEM-ANN model is accurate and effective for SQ evaluation of a low-frequency sound. The proposed hybrid approach can be used to simulate the acoustic behavior of an auditory system, which helps in revealing the mechanism of human auditory perception.

1. Introduction

In recent years, the sound quality evaluation (SQE), an acoustic behavior of human auditory system subjecting to a sound-related product, has become a very active research area. For the last few decades, a large attention has been given to SQE of vehicle noises (low-frequency sounds) [1–3]. A-weighted sound pressure level (SPL) is one of the most commonly used SQE indices for low-frequency vehicle nois. It has been found that the A-weighted SPL of a sound is not exactly the same as the sound being perceived. Thus, some psychoacoustical indices, such as the loudness, sharpness, roughness, annoyance, and pleasantness, have been studied to describe the subjective perception of a sound. The first model for loudness calculation was established by using the sound frequency spectra and the masking curves from some subjective tests [4]. Instead of the subjective tests, Stevens [5] introduced a concept of loudness index and proposed a loudness model based on the band-pass filter technique, where the transmission characteristics of external and middle ears were neglected. An excitation-level-based loudness model was presented by Zwicker and Fastl [6]. As this model considered the frequency selectivity in the cochlea, the Zwicker loudness model is closer to the auditory perception of humans and has been accepted by the standard ISO 532B [7]. Considering the transfer function of a sound in the external and middle ears, a loudness model based on the equivalent rectangular bandwidth (ERB) scale was established by Moore et al. [8]. In the Zwicker model, the sharpness can be directly obtained from the specific loudness values. The roughness can be calculated either by the Aure's, Fastl's, Sottek's methods, or using their improved versions [9,10]. Currently, only a few psychoacoustical indices, such as loudness, sharpness, roughness, fluctuation strength and tonality, have mathematical models. Except for A-weighted SPL and loudness, there are no other psychoacoustical parameters that have ISO standards. The standard ISO 532B provides a graphic method for calculating loudness and sharpness

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by using the one-third octave bands that have been proven effective for SQEs of the engine noise, interior noise and door-slam quality of a vehicle [11,12]. Thus, in this work, the A-weighting SPL, loudness and sharpness are selected as the target parameters in the hybrid modeling. In fact, the SQE involves in multi-disciplines, such as acoustics, mechanical dynamics, psychology, and physiology. The SQE procedure can be performed in two steps. The first is to obtain physical responses of the auditory system subjecting to external sound excitations. The second is to study the neural system response to the obtained physical signals.

To study the physical response of human ear to the sound excitations, the middle ear models using analog circuit method have been established [13–15]. Such methods can avoid the difficulty of study in vivo (or a specimen), but cannot reveal the exact dynamic characteristics of a human auditory system. Assuming the ossicles are rigid, a multi-rigid-body dynamics model of the human ear was established and used to calculate the structural vibration modes [16]. The assumption of rigid structure cannot give accurate results of the soft tissues, such as tympanic membrane, and ligament. Compared to the above methods, the finite element method (FEM) has significant advantages in simulating the human ear system. There are three modeling methods: (a) physical data measurement, (b) tissue sections and (c) computed tomography (CT) scanning. Utilizing the physically measured data, a FEM model of inner ear hair bundle was built for investigating the transfer characteristics of the hair cells [17]. Edward and Julian [18] established a three-dimensional (3D) FEM model of the cochlea and studied the interaction between the bone and lymph fluid. It has been found that it is difficult to construct a accurate model by physical measurement due to the extreme complexity and small size of the structures in the ear. In the past 20 years, the reverse forming technology of the human ear system has been widely discussed and applied in the biomedical engineering. Based on the tissue section data, the FEM models of the human ear canal, middle ear and cochlea were established. The sound transmission characteristics from the ear canal to the cochlea and the biomechanics in the middle ear are investigated [19–21]. A tympanic membrane FEM model was used to solve the equivalent problem of cochlear lymph fluid [22]. The tissue section method is effective in modeling and analyzing the soft tissues, but has a difficulty in data reconstruction and applications. Thus, in the recent years, the CT scanning method is adopted for obtaining the original data. Using the scanned CT data, the 3D FEM models of ossicular chain and middle ear were constructed for dynamic analysis of the ossicles in the middle ear [23–25]. Furthermore, a more complex FEM model including the ear canal, ossicular chain, middle ear cavity, and the cochlea was presented, in which the motion characteristics of a basilar membrane were studied [26]. From the above literature, it can be concluded that the FEM can be successfully applied for calculating the dynamic characteristics of the human ear, and may be used for sound transmission simulations. The previous studies are mainly focused on the human ear diseases and the corresponding hearing damage compensation devices. In this work, the FEM models of the auditory canal middle and ear tympanic membrane are built to reveal the sound transmission behavior, and thereby SQE of vehicle interior noise.

Due to the nonlinear feature of human auditory system, it is impossible to find an exact physical model to describe the perception response for all people. To map the sound features to auditory perception, some methods based on sound feature extraction and pattern classification have been recently proposed for SQE of vehicle noises. The time-frequency algorithms, such as short-time Fourier transform, discrete wavelet transform, wavelet packet analysis and Wigner-Ville distributions, were introduced into the SQE engineering for sound feature extraction [3,27]. To classify the sound patterns, an artificial neural network (ANN), support vector machine methods and their improved versions were used for SQ prediction [28–30]. These methods directly mapped the physical sound signals to their psychoacoustic parameters, which cannot reveal the sound transfer characteristics among the components in the human auditory system. Following the human hearing process, a novel method by combining the FEM and ANN models for acoustic behavior prediction of the human auditory system is developed in this paper. Compared to the in-situ methods, the FEM-ANN may be used to predict the acoustic behavior and SQE parameters from a human ear. This is a new attempt for SQE of a low-frequency sound (vehicle noise). The proposed model can reflect the sound transfer mechanism in the human hearing system, which is helpful for ear disease diagnosis and hearing repair in the bio-medical engineering.

2. Auditory perception process of human

The auditory perception process, which is related to the physiological structure of the human auditory system, is very complex. To build a FEM model of the human ear and obtain a reasonable hearing evaluation result, firstly, one needs to understand the structure and function of the auditory system. Fig. 1 shows the sound transmission path and the perception forming process in the auditory system. The human ear is composed of the external ear, middle ear and inner ear. A sound may be transmitted into the inner ear through the air and/or bone conductions, where the air conduction is primary transmission mode. The vibration of a sound source generates sound waves, which are collected by the auricula and then transferred to the tympanic membrane through the ear canal. The vibration of the tympanic membrane leads to vibrations of the ossicular chain (malleus, incus and stapes) in the middle ear. The stapes at the end of ossicular chain is connected with the entrance of inner ear (oval window). Thus, the vibration information is transferred from stapes footplate to lymph fluid in the inner-ear cochlea through the oval window. The traveling waves caused by the lymph disturbance may quickly spread throughout the cochlea, and thereby causing the movement of basement membrane [31]. The hair cells on the basement membrane convert the vibration signals into electrical signals, which may generate neural impulses in the auditory nerves. The neural impulses are further transferred to the auditory center in cerebral cortex through the nerve fibers. Thus, an auditory perception of the sound is finally created. In the present work, the sound transmission in the external ear and middle ear is calculated by using a

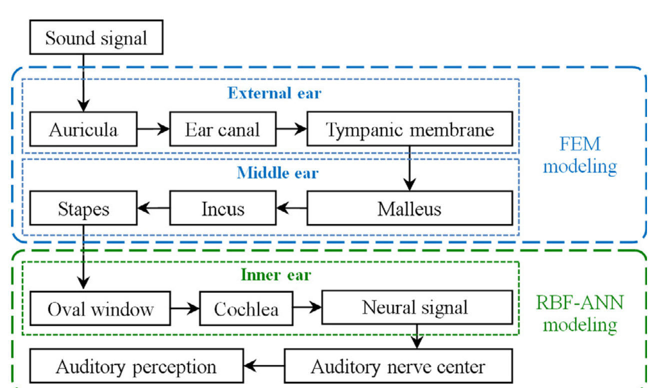

Fig. 1. The forming process of auditory perception in the human hearing system.