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Acoustic comfort evaluation modeling and improvement test of a forklift based on rank score comparison and multiple linear regression

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ABSTRACT

Aiming at the common problems of the engineering vehicles with high environment noise and poor acoustic comfort, this paper proposes an acoustic comfort subjective evaluation method based on rank score comparison (RSC) and develops a corresponding software system; it provides the solution method of evaluation modeling and improvement measure based on multiple linear regression (MLR). The actual application case of 50 noise samples from forklifts is presented to verify the feasibility and effectiveness of the RSC method. Through the subjective evaluation experiment, calculation of psychoacoustic parameters and data statistical tests, acoustic comfort evaluation model is established based on MLR. Consequently, the most significant parameter and improvement measure of acoustic comfort are obtained by means of sensitivity analysis and noise spectrum analysis. Finally, the improvement test of a target prototype is carried out and results indicate that the acoustic comfort has been improved obviously and the noise decibel level has met the industry standard requirement.

1. Introduction

As an important part of equipment industry, engineering machinery is widely used in transportation, mining and urban construction and so on. At present, the noise caused by the engineering machinery has already attracted the social attention. There is no doubt that noise has become a significant factor to measure the performance of engineering machinery. Indicated from practice, the high-decibel-level noise produced by engineering vehicles not only pollutes the surrounding environment, but also endangers the driver's physical and mental health [1]. With the development of living standard and inhabited environment quality, people have become more and more conscious of many details related their own health and quality of life. In the future, vehicle acoustic comfort will be a heated topic for research due to its closely connection to daily life. In the past research on vehicle noise reduction, A-weighted sound pressure level (ASPL) was generally taken into consideration as the main evaluation index. However, ASPL based on the equal loudness curve of 40 phon to correct the actual sound pressure only represents the human ear's feeling of low frequency sound pressure. And it thus cannot fully reflect the true feelings of the human ears to the actual sound [2]. Therefore, it is an urgent problem to be solved on how to evaluate and improve the acoustic comfort of engineering vehicles.

Acoustic comfort describes the psychological perceptual procedure of human ear to sound and subjective judgments, whose widely recognized definition in academia was proposed by German scholars [3]. Relative existing literatures [4–9] show that studies of acoustic comfort are mainly focused on acoustic subjective and objective evaluations and their mathematical mapping, among which the commonly used subjective evaluation methods mainly include rank order, grade score, paired comparison and semantic differential; the objective evaluation of acoustic comfort is to calculate and analyze psychoacoustic parameters including loudness, sharpness, roughness and so on, which comprehensively consider the human psychological responses and acoustic perception characteristics and reflect the difference of subjective feeling caused by different sound signals; the mathematical modeling method to establish the mapping function of psychoacoustic objective parameters and subjective evaluation mainly uses the MLR and back propagation neural network (BPNN) algorithm.

MLR is based on the statistical analysis of multi-group dataset, which can directly and quickly obtain the correlation and fitting degree of the dataset, and the prediction accuracy is reliable through regression tests. BPNN, a kind of multi-layer forward feedback neural network with error back propagation, has certain self-adaptive ability and fault tolerance while the prediction model established by this method is affected by the network structure parameters such as the number of layers

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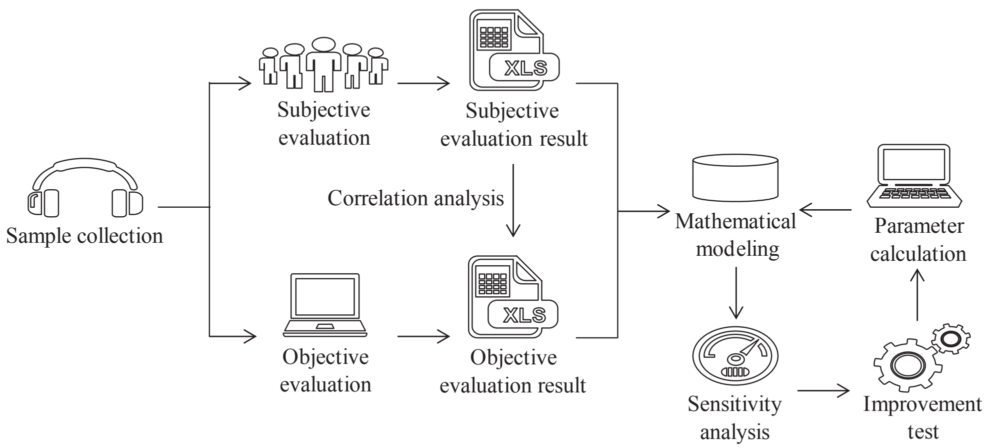

Fig. 1. Proposed method for acoustic comfort modeling and improving in actual engineering application.

and neurons, and the stability is relatively poor. In addition, the current research of acoustic comfort is primarily applied in passenger car and electrical industries, but it is almost blank in the field of engineering machinery. Therefore, taking the external radiation noise samples from forklifts as the research object, this paper establishes the acoustic comfort prediction model through the MLR analysis and carries out the improving test to make the acoustic comfort of the target prototype better.

2. Solution method

In order to solve the problem in practical engineering, the proposed method is described schematically in Fig. 1. Detailed steps are as follows: (1) Acquire high-precision sound samples by specialized equipment, SQuadriga II, which considers binaural effect to truly collect the original sound [10]. (2) Organize and train several people to score the samples by grade evaluation method, and simultaneously select and calculate psychoacoustic parameters for objective evaluation. (3) Obtain subjective and objective evaluation results with the reliability and validity tests of data by means of SPSS (Statistical Package for the Social Science) statistics analysis. (4) Adopt MLR approach to set up the mathematical model of subjective and objective evaluation results, and then determine the main psychoacoustic parameter through sensitivity analysis. (5) After studying the corresponding relationship between the main parameter and noise frequency spectrums, the improvement measure of acoustic comfort can be put forward. (6) On these grounds, the improvement test of application prototype is performed, after which psychoacoustic parameters of new sound samples collected by the binaural acquisition equipment are calculated and brought into the established formula to obtain the predicted value of acoustic comfort.

3. Subjective evaluation experiment

Five traditional internal combustion forklifts from different manufacturers widely used in the market were selected as experimental objects. Under the premise that vehicle components and systems were in good working condition, all the prototypes were operated at constant speeds of the idle speed and rated speed. It should be noted that test environment around a few hundred meters away is barrier free civil buildings and have no external noise interference. In the test, the 8-channel data acquisition system of SQuadriga II was leveraged for noise signal acquisition. Four measuring points are located one meter away from the body surface of experimental vehicle, and the fifth measuring point is situated along the driver's ear.

Due to the consideration that people may feel tired in longer sample length more easily, several pretreatments must be performed prior to the subjective evaluation experiment, involving such tasks as segmentation, interception and screening. Therefore, 50 noise samples with a length of 5 s are ultimately determined as the subjective evaluation objects.

It is well known that the noise decibel level produced by engineering vehicles is much higher than that of surrounding environment in practical application. Therefore, people can feel aurally uncomfortable and irritable easily. Meanwhile, annoyance is a parameter which can comprehensively reflects the degree of discomfort caused by specific noise signals to human hearing. In this experiment, therefore, annoyance was selected to be the subjective evaluation index.

Each mentioned subjective evaluation method has its own characteristics and shortcomings; for instance, the traditional method of grade score has difficulty in determining the evaluation grade value of noise samples. Considering the large number of samples and the data need for later subjective and objective modeling, grade score method was improved in this paper. Plus, the subjective evaluation index was divided into 10 grades, in which the noise annoyance was further subdivided into 5 parts from low to high, and each part had two grades, as shown in Table 1.

In order to make people better grasp the grade scores, several comparison samples were added and their corresponding annoyance values were assigned according to pre-evaluation results. Consequently, based on the aforementioned method, a practical evaluation system was designed and built by MATLAB graphical user interface (GUI) development platform. It has been indicated that 20 evaluators can meet requirement for most evaluation experiment of statistical analysis [11]. In this evaluation experiment, a total of 40 people were formed by drivers, engineers, acoustics experts, master and doctor graduate students who had experience in vehicle noise with normal hearing. In the process of evaluation, evaluators repeatedly listened to comparison samples at first and focused on corresponding grades, and then started to playback all the noise samples and made a clear grade judgment according to subjective feelings.

However, because of the subjectivity of evaluation decision, the consistency of evaluation results needs to be well checked for the further application to mathematical modeling. Findings in current reports [12,13] indicate that the Spearman correlation coefficient and K-mean clustering are availably utilized to measure and prove the reliability and validity of acoustic comfort evaluation results. Correlation analysis reveals that the average correlation coefficients of all evaluators are above 0.7, which shows a satisfied consistency and reliability obtained by the improved evaluation method. To ensure the representation of the

Table 1
Grade setting of the subjective evaluation index.

Annoyance	Not at all		A little		Partly		Rather		Awfully	
Grade	1	2	3	4	5	6	7	8	9	10