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by Zihui Xiao

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Research Proposal Report based on Automobile
Sound Quality and Sound Design

by

Zihui XIAO

Supervisor: Dr Gareth

Second Marker:

Project submitted as part of the requirements for
the award of MSc Data and Artificial Intelligence

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DECLARATION

I, Zihui XIAO declare that I am the sole author of this Project; that all references cited have been consulted; that I have conducted all work of which this is a record, and that the finished work lies within the prescribed word limits.

This work has not previously been accepted as part of any other degree submission.

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Abstract

In order to study the evaluation of automobile sound quality and sound design, this paper selects three representative vehicles of different models (logo 4008, BMW I8 and Audi R8) that apply active sound design (ASD) technology to carry out interior noise test, collects noise samples at various orders, different pedal openings and ASD modes, and carries out data processing and working condition analysis on the collected sound samples. Then based on the grade scoring method, the subjective evaluation is scored, the objective parameters are calculated and the multiple linear regression model is established. Based on this, the process and method of target sound design are proposed. In addition, EEG signals based on sound stimulation were collected and analyzed. The results show that the ASD modes of different vehicles have different effects on their noise, and the order characteristics and pedal opening also affect their sound quality. The multiple linear regression model has a good fitting degree, which can be used for sound design to meet the requirements of design objectives. At the same time, it also proves the feasibility of evaluating sound quality with EEG signals. Finally, some deficiencies in this study are described, and the future research is prospected.

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1. Introduction

With the development of society and national industrial level, major automobile enterprises in various countries have completed the transformation from pursuing the growth of automobile production capacity to improving the quality of vehicle models. As one of the most important indicators to measure the quality of automobiles, the research on the noise and vibration performance of automobiles has developed from the basic vibration and noise amplitude control to the sound quality control stage aiming at eliminating annoyance sound and improving comfort.

The evaluation of automobile sound quality reflects people's subjective feeling of automobile sound. Its research objects mainly include automobile sound characteristics, listeners and perceived environment. Usually, the evaluation of automobile sound quality needs to be objectively quantified through language description. The evaluation methods mainly include subjective evaluation and objective evaluation. In terms of subjective evaluation, people are the final receivers of voices, and the evaluation results are affected by people's own emotions, experiences, cognition and environment. Evaluators tend to recall, conceptualize and describe their experiences through language, which makes it impossible to intuitively reflect the preference characteristics of people on the scale. In addition, the evaluation of non acoustic professionals can easily lead to the deviation between the evaluation results and the real feelings, and it is difficult to reach an agreement.

Objective evaluation is based on objective quantitative indicators to map the subjective feelings of the evaluator on the sound, mainly including physical acoustic parameters and psychoacoustic parameters. Among them, physical acoustic parameters mainly focus on the overall level of noise, lacking comprehensive evaluation. Similarly, psychoacoustic parameters are mainly used to characterize people's specific perception of sound, and cannot map the overall preference. Therefore, most of the objective evaluation indicators used to extract noise features can not fully describe the perceptual responses of all individuals. In order to improve the accuracy of automobile sound quality evaluation, domestic and foreign researchers have also tried to establish a mapping relationship model between subjective and objective evaluation results using mathematical models. However, most of the current evaluation models still only analyze people's subjective feelings

about sound quality from the perspective of physical acoustics and psychoacoustics, which is not comprehensive enough, and most of the sound quality evaluation models built are simple in structure. It is difficult to reflect the complex relationship between sound signal characteristics and human subjective perception.

In recent years, with the further research of EEG in emotion recognition, it is possible to evaluate sound quality based on EEG. As a physiological feature that can reflect individual differences, EEG signals can objectively reflect the intuitive feelings of different evaluators on sound. EEG signals can be used to realize the division of diversified sound quality types, so as to realize the accurate evaluation of conceptualized and abstract sounds, and provide a strong basis for the application of EEG signals to the proposal of physiological and acoustic indicators of automobile sound quality; Through the research of EEG classification model, it provides an effective research foundation for switching preferred driving sound modes through EEG signals in the future.

The active sound design technology of automobile is based on the pre-designed automobile sound that meets the "sound interest" needs and pleasant experience of drivers and passengers, reasonably constructs the active sound synthesis algorithm and formulates the active sound control strategy that matches the dynamic characteristics of the target vehicle model, and uses the active sound generate (ASG) controller to track the driving status of the vehicle in real time (such as accelerator pedal opening, vehicle speed, rotational speed and other information). It is a new technology that drives vehicle speakers or external speakers to actively emit target sound. Among them, target sound design is the primary research content of ASD technology. How to ensure that the pre designed sound can meet the needs of users for sound quality is the core of ASD technology, and automobile sound quality evaluation is the premise to guide target sound design.

The active design of target sound that meets the requirements of sound quality evaluation is a key factor affecting the differentiation of electric vehicle brands, which can make users have a profound sense of satisfaction and brand identity for automobile products. In order to improve the acoustic characteristics of electric vehicles in the future, avoid the homogenization of electric vehicle products, and improve the brand effect, the demand for active sound design in electric vehicles,

which is oriented to improve the competitiveness of automobile products, is also growing with the aim of making breakthroughs in ASD core technologies such as target sound design, active sound synthesis algorithm, active sound control method and real vehicle ASG system development.

In this paper, the interior noise of three vehicles with different models using active sound design (ASD) technology, namely the logo 4008, BMW I8 and Audi R8, was tested, and the collected results were analyzed by data processing and working conditions, to explore the impact of different steps and pedal opening on the automobile noise. Then, the car noise samples measured in the experiment are scored by subjective evaluation and eight commonly used objective parameters are calculated. On this basis, a linear regression model of subjective and objective evaluation is established, and based on this, the process and method of target sound design are proposed. In addition, EEG signals under sound stimulation were also collected, and EEG data preprocessing, time-domain features and frequency-domain features were extracted. The feasibility of evaluating sound quality with EEG signals was analyzed.

This paper is divided into seven chapters. The first part briefly introduces the research background and significance; The second chapter mainly reviews some domestic and foreign literatures on the research of automobile sound quality and sound design; The third chapter introduces the methods used in the research and the contents related to the experimental design, mainly including the methods and experimental design ideas and steps of the collection of automobile noise samples, subjective and objective evaluation tests, and EEG signal collection based on sound stimulation; On the basis of the third chapter, the fourth chapter describes in more detail the instruments and equipment used in the test process and some data collected therefrom; In the fifth chapter, the collected test data are processed and analyzed; The sixth chapter draws some conclusions from the data analysis of the fifth chapter; The last chapter summarizes the experimental research and conclusions, discusses the defects and deficiencies in this study, and looks forward to the future.

2. Literature review

2.1 Relevant literature on automobile sound quality evaluation

In the early 1990s, sound quality was widely used in the field of automobile noise. As a subjective feeling closely related to the evaluators, various subjective evaluation methods of sound quality came into being. Tsuge K[1] and others of Toyota Motor Company first mentioned vehicle sound quality in the field of noise control in the study of acceleration noise of passenger cars. Since then, the concept of sound quality has appeared in the research field of vehicle NVH. Subsequently, Blauert J [2] defined sound quality in detail at the international noise conference, that is, sound quality is the evaluation of sound suitability in the connotation of specific technical objectives or tasks. Car sound quality is a comprehensive study of many factors, which mainly focuses on the evaluation of the target sound that conforms to car acoustic characteristics. Its research objects include car sound characteristics, evaluators and test environment.

The evaluation methods of automobile sound quality mainly include subjective evaluation and objective evaluation. In terms of subjective evaluation, the commonly used evaluation methods include: pairwise comparison method, grade evaluation method, semantic subdivision method, etc. The application scope of different evaluation methods is different, so different evaluation methods should be selected according to the inherent attributes of the sound samples to be evaluated, the experience of the evaluators, the evaluation environment, etc., or a new evaluation method for automobile sound quality should be proposed in combination with the advantages and disadvantages of existing evaluation methods.

In 1997, Clark D [3] and others of Ford company elaborated on the advantages, disadvantages and application scope of different subjective evaluation methods, systematically compared the differences between various subjective evaluation methods, and confirmed that semantic subdivision method and pairwise comparison method have higher accuracy than other subjective evaluation methods. In 1991, Schiffbänker H et al [4] of AVL company in Austria collected more than 60 engine noises with good sound quality, combined with subjective and objective evaluation, summarized 8 kinds of subjective evaluation indicators and 48 objective evaluation indicators, and proposed a complete set of evaluation methods for engine noise

sound quality. On the basis of this study, Japanese scholar Noumura K[5] further improved the sound quality evaluation method, expanding the 8 categories of indicators proposed by Schiffbänker H[4] and others to 12 categories.. In 2003, Kousuke N et al [6] analyzed the subjective feelings of evaluators from different countries, such as the United States, Germany and Japan, on the sound of cars from the perspective of the selection of evaluators of different nationalities, and concluded that there were differences in the perception of the same sound among evaluators in different regions. Murata H et al [7] showed through research that the interior sound quality can be described by two subjective perception indicators, comfort and power. Sato N et al [8] constructed four groups of objective evaluation indexes to evaluate the comfort of diesel engine radiated noise, namely "high-frequency component", "high-frequency sound pressure level", "spectrum feature" and "peak factor", and used loudness index to evaluate the sense of strength. Noriyoshi T [9] and others proposed an evaluation method for the interior noise quality in the process of automobile acceleration, defined pleasure and passion as the main evaluation indicators, and explored the correlation between the interior acceleration sound quality and sound acoustic characteristics through organizing subjective scoring tests, so as to achieve the guidance of automobile sound design.

Domestic and foreign scholars have continuously optimized various subjective and objective evaluation methods of sound quality from the aspects of time complexity and evaluation accuracy, and built subjective and objective models using artificial intelligence algorithms, and improved the accuracy of the models using optimization algorithms. Although the traditional sound quality evaluation method has certain accuracy and effectiveness in sound quality evaluation, it also has some defects. Traditional subjective evaluation methods require evaluators to make judgments according to their own subjective feelings, so their evaluation results are affected by the evaluators' own personality, preferences, emotions, experiences and other aspects, so individual evaluation results inevitably have some particularity, and it is difficult to form a unified and standardized measurement system; While the traditional objective evaluation method can quantify sound characteristics by physical parameters, it is difficult to correspond with the conceptualized and abstract sound quality evaluation experience. In general, the traditional sound quality evaluation is based on the subjective perception of the human ear. The subjective

evaluation test is organized to describe the sound attributes in language, and the evaluator describes the auditory perception through language recall and conceptualization. However, for the evaluators with experience in soundology, it is difficult to use semantic subdivision method, pairwise comparison method and other methods to evaluate the conceptualized sound quality.

In order to solve the defects of traditional sound quality evaluation methods and avoid the above problems, physiological acoustic indicators have become a new focus of researchers. The physiological index energizes various physical functions of people and objectively describes the subjective feelings of people in the face of sound stimuli. Wang Z [10] and others proposed an objective evaluation method of vehicle interior noise based on human ear basement membrane displacement (smvbm_{dr}) as a physiological and acoustic index and combined with BP neural model. By calculating the statistical average of basement membrane displacement response, a feature matrix based on human ear basement membrane displacement is established. With the traditional psychoacoustic index and the extracted feature matrix as inputs, a BP neural network model for vehicle interior noise sound quality evaluation is established. This model can be used as an effective physiological and acoustic index to objectively evaluate the sound quality of vehicle interior noise. Compared with the traditional psychoacoustic measurement method, this measurement method can evaluate the sound quality of vehicle interior noise more effectively and accurately.

In addition, there are studies on sound quality evaluation based on EEG, ECG, EDA and PPG. At present, the physiological indicators that are widely recognized, not affected by cultural differences, and can objectively describe brain cognitive activities are mainly EEG signals. With the development of EEG signal related technology, it is possible to combine EEG signal with acoustic technology and use it as an index of automobile sound quality evaluation to describe and predict people's subjective feeling of sound with EEG signal.

Mazza F [11] and others summarized some common physiological measurement methods for emotional evaluation, such as heart and respiratory rhythm, electroencephalogram (EEG) and skin electrical resistance (GSR), as well as infrared thermography or laser Doppler perfusion monitoring (IDPM), and verified through

experiments that these methods have high accuracy in emotional judgment; Debener [12] and others directly compared the classical EEG cap device with the new periauricular electrode array (cEEGrid), further proving the feasibility of paraauricular EEG recording; Xu Z [13] and others used EEG signals and functional near-infrared signals (fNIRS) to describe the response of brain regions to sound. They found that the brain responses of subjects to different sound types were different. Under the same sound pressure level, the energy value response of fNIRS in brain regions with different audio data also showed regular changes; Stuldreher I V [14] and others compared and proved the validity of physiological synchronization (PS) of electroencephalogram (EEG), electrocutaneous activity (EDA) and electrocardiogram heartbeat interval (IBI) as an evaluation index of sound quality.

The voice quality evaluation system based on the data processing grouping method (GMDH) type neural network [15] uses the same frequency transformation as the traditional method, but extracts EEG differences between such voice qualities by creating a GMDH type neural network that outputs a value, improves the separation of feature scores, and improves the recognition rate. From 2014 to 2018, Mehta K et al [16-19] continuously explored the method of measuring and processing EEG signals. They first analyzed the entire transmission chain of stimulus generation, human brain processing and EEG sensors as a time-varying nonlinear communication channel (ERP channel) with memory by using mutual information (MI) as a measurement method, and directly measured the subjects' EEG responses through high-resolution EEG, verifying its feasibility. On this basis, the recorded EEG measurements are modeled using the multi-dimensional Gaussian mixture model (GMM). The MI results show that there is a great correlation between the actual and perceived audio quality. Then a causal information theory framework is proposed to measure the information flow between EEG sensors in different regions of interest (ROI) on the cerebral cortex. This new causal bi-directional information (CBI) measure is defined as an improvement on the standard directional information measure. CBI can be intuitively interpreted as a bi-directional causal correction of directional information. Compared with the use of standard directional information measures, CBI can better distinguish perceptual audio quality.

Sawata R [20] et al proposed an audio feature method that reflects people's preference for music based on EEG signal mapping. First, the best EEG feature

signal is determined by mrmr algorithm; Then the correlation between EEG features and audio features is constructed by using nuclear canonical correlation analysis (CCA) to determine the best audio features; Then, based on the determined audio features, the SVM classifier is used to recognize people's preference for music. Geng B and others [21] proposed the method of measuring the noise limit using the directed transfer function (DTF) transformation to study the noise perception limit of people. By constructing the brain connection diagram, the weighted clustering method was used to obtain the perception limit of people to audio noise in different scenarios and the validity of the results was verified. Akiyama A [22] and others took newborn babies as experimental subjects. The subjects wear electrode caps in the laboratory with good sound insulation effect and collect their EEG signals under audio stimulation in different scenes. In addition, most of the experiments also require the subjects to carry out subjective evaluation experiments of sound quality or some other experiments after collecting EEG signals, and use sorting method, pairwise comparison method, grade scoring method or semantic subdivision method to subjectively evaluate sound samples. Maiorana E and others [23] proposed an automatic artifact elimination strategy based on blind source separation (BSS) and sample entropy estimation (SE), which can effectively remove unnecessary noise in EEG data; Garvanov I and others [24] proposed a denoising algorithm based on the combination of wavelet transform, threshold processing and wavelet inverse transform, which effectively eliminated noise and retained information; K. A. Robbins and others [25] evaluated four preprocessing methods, including two ICA based preprocessing methods (large and Mara) and two different pseudo shadow spatial reconstruction (ASR), as well as the difference in time domain and spectrum domain of the remaining signal after eliminating the blink artifact. They found that small changes may also lead to differences and have a large impact on specific parts of the signal.

2.2 relevant literature on automobile sound design

The ultimate purpose of sound quality evaluation is to guide the positive design of automobile sound. For traditional fuel vehicles, by optimizing the structural design of transmission system, power system and intake and exhaust system, we can

achieve a variety of noise levels in the vehicle, create a variety of different sound qualities, such as power sense and luxury sense, and realize the sound design of automobile brands.

In 2001, Scheuren J [26] and others proposed the concept of active sound design and active sound generation of automobiles, and defined the ASD technology of automobiles as a new technology that actively generates target sounds inside and outside automobiles through electronics and sound systems. In 2010, Schirmacher R et al [27] discussed the research status and global industrial application of active noise control (ANC) and active sound design technology, showed the application status of ANC and ASD technologies in the field of automotive acoustic design, and looked forward to their prospects for realizing broadband noise elimination on roads and active design of internal and external sounds of electric vehicles. In 2011, Audrain P et al [28] of Hutchinson company designed an active sound control system based on an electronic exciter, which was successfully applied to electric vehicles and hybrid vehicles to achieve feedback on the acoustic perception of drivers or pedestrians according to different driving conditions of vehicles, and ensure driving safety while realizing driving passion.

In 2009, Hirate N and others [29] discussed in detail the sound design process of a 6-cylinder SUV: first, 40 American evaluators were organized to evaluate the sound of the car, and proposed to define the acceleration sound of the car from the three angles of order distribution, frequency balance and linearity. Then, the forward design of the sound quality of the car with a sense of motion was realized from the perspective of structural optimization of the intake and exhaust systems, engine mounts and other parts of the car. Hiscutt P et al [30] pointed out that the modulation of the main order and harmonious order of the car sound affects the quality of the motion sound. Among them, the low-frequency half order design can be paid attention to to achieve the low-frequency sense, and the deep sense can be realized through the design of even orders such as the 4th and 6th orders. The middle and high frequency 8th, 10th and 12th orders will affect the hollow sense. In 2014, Chang K et al [31] systematically studied the process of luxury sound quality design of automobiles from three perspectives: the dynamic characteristics of sound changing with speed, the balance of order frequency, and the harmony of order ratio. Maunder M and others [32] designed the sound gain table of the vehicle under

different driving conditions, and proposed to use the intake active sound generation device to realize the active sound design of the dynamic sound quality in the vehicle.

In 2014, Gwak D Y and others [33] carried out research on active sound design and subjective sound perception, proposed a method to improve the noise quality in electric vehicles by enhancing the traditional engine order infrasound signal, and built an in vehicle sound evaluation test bench for dynamic driving of electric vehicles. In the same year, Genuit K and Fiebig A [34] discussed the opportunities and challenges of the current active sound design technology in electric vehicles, and optimized the car sound that meets the needs of the market and users. Sarrazin M and others [35] proposed a virtual sound synthesis algorithm for electric vehicles and hybrid vehicles. Based on the collected target sound signals, the voice samples are post processed from three angles: order extraction, broadband noise synthesis and sound superposition, and the target sound samples are synthesized by harmonic superposition.

Automobile active sound synthesis algorithm is the key to achieve the target sound design through active utterance control technology. At present, synthesis algorithms mainly include sound particle algorithm and harmonic algorithm. These two algorithms have their own advantages and disadvantages, and there are also many researches in this area at present. Van Rensburg T J et al [36] proposed to model the engine sound by using the phase vocoder to simulate the engine sound at different vehicle speeds and ensure the coherence and naturalness of the synthesized sound in view of the shortage of the linear interpolation between the engine sound samples to simulate the engine sound. Jagla J and others [37] solved the unnatural sound transition caused by different harmonic components at the splicing of sound particles by building a tower based window and using overlap phase addition to overlap and splice sound particles. Although some optimization algorithms for sound particle synthesis have been proposed by scholars at present, most of them are complicated in calculation, and it is difficult to realize the active utterance technology to match the needs of complex and variable driving conditions of vehicles.

3. Research methods and experimental design

This study mainly involves three aspects of experimental design, namely, the vibration and noise sample collection test of the test vehicle applying ASD technology under different working conditions, the subjective and objective evaluation test of the sound sample, and the EEG signal collection test based on sound stimulation.

3.1 Noise and vibration test of traditional internal combustion engine vehicles

The test site is selected on the mute hub bench in the semi anechoic room of the whole vehicle and on the road of the real vehicle to test the internal noise, engine noise and intake and exhaust noise of the test vehicle under different working conditions. Sensors such as microphone and acceleration are arranged in the vehicle. The driver in the car wears headphones and synchronously collects ignition coil signals and noise and vibration signals on the driver's seat through LMS \ head data acquisition system to obtain sound samples under different working conditions. The test conditions include constant speed, acceleration, deceleration, idling, etc. the rapid acceleration noise test is conducted in gear 2 or gear 3 according to the number of gears of the selected model. When studying the correlation between the driver's operation behavior and the sound signal in the vehicle, the collected signals also include the signals of the vehicle's operating state parameters, such as vehicle speed, rotational speed, accelerator pedal opening, etc.

The working conditions and performance verification of the real vehicle test mainly include: the evaluation and compensation of the difference between the playback sound of the on-board speaker system and the playback effect of the off-line headphones, including the collection of the on-board frequency response characteristics and the calibration of the volume; Engine order ratio, sound pressure level of each order noise and corresponding reverberation parameter calibration; Sound gain calibration under different working conditions, such as different opening, speed and other conditions; As well as the evaluation and optimization of the played synthesized sound quality.

3.2 Subjective and objective evaluation test of sound quality

Develop a subjective and objective evaluation test scheme to evaluate the obtained sound samples. The subjective evaluation test was conducted in the listening room, and the sound samples were played back in sequence with high fidelity headphones. Taking into account the cultural background, subjective habits, preferences and cultivation of the evaluators, some NVH experts, music theory experts, engineers or about 15-25 teachers and students at school are invited to participate in the evaluation. Before the subjective evaluation, all sound samples shall be treated with equal sound and length, and the ten grade evaluation table shall be divided according to the subjective feeling and strength, and each evaluator shall be organized to audition the evaluated sound samples. Among them, 2-4 points represent quiet sound quality, 4-6 points mean that the sound is mild, 6-8 points mean that the reviewer thinks that the sound sample has a sense of motion, 8-9 points mean that the sound is noisy, and 10 points mean that people can't bear the sound. During the evaluation process, the system automatically plays each sound sample, and the playback interval is set at 5S between each sound sample. Each evaluator uses the grade scoring method to score the sound quality of the sound sample. At the same time, calculate the objective parameters of the sound sample, such as loudness, sharpness, roughness, AI index, Bi index, MI index, volatility, linearity, etc.

3.3 Experimental design of brain cognitive mechanism for sound quality

The brain cognitive test was conducted in the semi anechoic room under the stimulation of automobile sound; In view of the lack of brain cognitive experimental paradigm in auditory stimulation, an experimental design idea considering the semantic diversity and individual differences of car sound samples is proposed; Through different semantic levels of sound quality, the sensitivity of different personality traits to sound stimuli was studied, and the effects of audio characteristics such as spectral centroid, spectral flux, root mean square value and zero crossing rate on EEG were analyzed.

The statistical mean of the physiological artifact data is zeroed and whitened by centralization, so that the covariance of the observation matrix is transformed into a

unit matrix and the correlation between the observation vectors is reduced; Independent component analysis (ICA) is used to decompose the multivariate signal into independent and non normal source signals, and the signal after artifact removal is obtained by inverse transform of ICA; The wavelet reconstruction method is used to reconstruct the de artifact EEG signal to obtain the desired EEG signal.

In time domain, event-related potential (ERP) signal statistics, energy, power, high-order zero crossing analysis, Hjorth parameter features, instability index and fractal dimension are extracted as time domain features. In the frequency domain, the frequency band is divided into five sub bands (δ 、 θ 、 α 、 β 、 γ) , Extract the power and power spectral density of each frequency band respectively, and calculate the mean, maximum, variance and other statistics of the internal power spectral density of each frequency band as frequency domain characteristics. In the time-frequency domain, confirm the time corresponding to each frequency-domain component of the non-stationary signal, and obtain the time-frequency characteristics by using short-time Fourier transform (STFT) or wavelet transform (WT); In the spatial domain, after extracting the frequency-domain features on each electrode, the common spatial pattern (CSP) and other algorithms are combined with the spatial domain to calculate the space-frequency domain features; The feature sets of EEG signals that are strongly correlated with subjective indicators of sound quality are established from four aspects: time domain, frequency domain, time-frequency domain and spatial domain.

Clustering EEG features and subjective evaluation indicators of sound quality based on fuzzy c-means clustering algorithm, obtaining the membership of each sample data to all class centers by optimizing the objective function, so as to determine the class of sample data, and determine the mapping relationship model between EEG features and subjective evaluation indicators; Using the ERP Superposition Technology Based on time series and the EEG signal analysis method based on band energy, the rules of EEG band change, brain area change and emotional induction under the stimulation of automobile sound are analyzed. The sound samples of the sample library mainly come from the experimental collection and the audio of online games such as automobiles. Before the start of the test, it is also necessary to play back all samples for audition and equal sound processing, and

use editing software to intercept the sound samples at the same length. At the same time, the intercepted samples are processed gradually in and out from the beginning to the end, so as to ensure the smoothness of the sound when playing back the sound. After completing the experiment, we also need to preprocess the collected EEG signal data.

4. Data collection

4.1 collection of automobile sound sample data

The target models used in the experimental test are the pe4008 (with an annual output of 1.6T \ V4 in 2013), the BMW I8 (with an annual output of 1.5T \ V3 in 2016) plug-in hybrid electric vehicle and the Audi R8 (with an annual output of 5.2t \ V10 in 2017) plug-in hybrid electric vehicle. The three test models are shown in Figure 1.



(a) (b) (c)

Figure 1 test models: (a) logo 4008 (b) BMW I8 (c) Audi R8

Measurement tools include data acquisition system, sound quality analysis equipment, noise source positioning equipment, sensors and other test equipment, as shown in Fig 2. Among them, the data acquisition system equipment includes the squadriga II data acquisition system; Sound quality analysis equipment includes head binaural artificial head and binaural sound collection and playback system; Sensors include gras microphone, gras microphone calibrator, gras sound intensity sensor, etc; Other test equipment include engine noise source separation system, ANC active noise elimination system, ASD active sound generation system, charge amplifier, devotron data acquisition system, signal integrator, etc.



(a) (b)

Figure 2 test equipment: (a) head binaural artificial head (b) gras microphone

On the straight asphalt road with small traffic flow, the radiated noise of the

engine body, the noise of the exhaust pipe orifice and the noise of the driver's right ear of the above three target models under the condition of full throttle acceleration in the third gear were collected. BMW I8 and Audi R8 are both in sports mode, and the test speed range is about 0-120km / h.

Collect the internal noise of the target vehicle under different gear and full throttle acceleration conditions, use the digital artificial head HMS iv.0 of head acoustics to collect the noise at the front passenger's seat, and use the collection software head recorder to connect the 8-channel squadriga II data acquisition controller for test data collection. At the same time, during the acquisition process, set the squadriga II as an independent acquisition mode, and set the equalization mode of HMS iv.0 through the touch-screen mode to equalize the collected data, so that the subsequent playback sound fits the sound in the real acquisition scene as much as possible, and is stored in the memory card of the squadriga II in real time.

4.2 Collection of subjective and objective evaluation result data of sound quality

In this experiment, grade scoring method was used for subjective evaluation. The evaluation grade scale and its corresponding semantics are shown in Table 1.

Table 1 10 rating scale

Score	sportiness
2-4	quiet
4-6	mild
6-8	with a sense of motion
8-9	noisy
10	unacceptable

Eight objective parameters are selected, which are loudness, sharpness, roughness, AI index, Bi index, MI index, volatility and linearity. The objective parameter values and subjective evaluation results are shown in Table 2.

Table 2 subjective and objective evaluation results

Sample number	loudness (sone)	sharpness (acum)	roughness (asper)	AI index (%)	BI index	MI index	volatility	linearity	subjective score
1	25.74	0.49	0.29	77.07	6.8053	0.0049	0.159	1.0686	5.71
2	32.35	0.44	0.4	75.8	4.4677	0.0083	0.133	2.1832	7.02
3	50.14	0.47	0.39	68.03	7.9232	0.0074	0.133	3.8367	7.43
4	23.03	0.51	0.21	78.67	11.3264	0.0099	0.134	2.1930	7.42
5	10.36	0.35	0.26	94.15	11.3320	0.0042	0.216	0.4465	6.78
6	26.04	0.48	0.24	77.22	6.5799	0.0083	0.154	2.4741	5.83
7	32.44	0.44	0.39	75.71	4.9693	0.0037	0.151	1.9163	7.81
8	46.88	0.44	0.36	71.19	6.9267	0.0045	0.137	4.7006	7.54
9	11.65	0.32	0.15	94.82	12.9773	0.0095	0.201	0.3830	8.71
10	18.59	0.42	0.26	84.08	6.1786	0.0079	0.146	5.2861	5.44
11	23.86	0.41	0.34	79.63	3.3021	0.0044	0.136	1.7285	9.03
12	29.89	0.44	0.31	75.85	5.1981	0.0068	0.147	5.0566	7.07
13	25.78	0.50	0.30	76.15	6.9614	0.0048	0.158	1.1367	5.61
14	34.21	0.45	0.42	75.03	4.5123	0.0082	0.134	2.2455	6.86
15	51.53	0.48	0.40	67.27	8.0117	0.0073	0.133	3.9014	7.32
16	22.16	0.50	0.20	79.31	11.2776	0.0099	0.135	2.1023	7.52
17	10.01	0.34	0.25	94.87	11.2823	0.0043	0.215	0.3911	6.92
18	25.28	0.47	0.23	78.20	6.5132	0.0084	0.155	2.4123	5.91
19	34.13	0.45	0.40	75.01	5.0177	0.0036	0.152	1.9655	7.62
20	47.88	0.45	0.37	70.63	6.9976	0.0044	0.138	4.7765	7.41
21	13.01	0.33	0.16	94.27	13.0377	0.0094	0.201	0.4213	8.61
22	16.67	0.41	0.25	84.76	6.1153	0.0080	0.145	5.1867	5.60
23	24.23	0.42	0.35	78.98	3.3628	0.0043	0.135	1.8034	8.95
24	27.61	0.43	0.30	76.29	5.1297	0.0069	0.146	4.9617	7.35

4.3 Acquisition of EEG signals induced by sound

EEG signal is a kind of bioelectric signal with weak signal and easy to be

interfered by the outside world. In the process of acquisition, we must ensure that there is less background noise in the environment. Therefore, the whole experiment was conducted in the semi anechoic chamber. The background noise of the semi anechoic chamber is less than 20dB (a) and the cutoff frequency is less than 63Hz, which fully meets the experimental conditions. The EEG signal acquisition equipment adopts actichimp EEG acquisition instrument developed by German brain products company. As shown in Figure 3, the data acquisition system directly realizes real-time data transmission with the computer through USB.



Figure 3 EEG collector

In order to reduce the amount of data and ensure that the EEG signal has sufficient spatial resolution, the EEG signal is collected through the Ag / AgCl EEG cap in the experiment. The EEG cap has 64 electrodes, and the electrode arrangement meets the international lead 10-20 standard [38], as shown in Fig 4. First, four anatomical points are determined on the head: the nasal root, the occipital eminence, and the bilateral preauricular points (at the preauricular notch). The sagittal line and the coronal line are determined from these four points, and the distance between the electrodes is 10% - 20%. Odd numbers on the left and even numbers on the right. The intersection of the two on the top of the head is the position of the Cz (central midline) electrode. FPz (midline of frontal pole) is located 10% backward from the nasal root. Every 20% backward from FPz is the location of one electrode, which is Fz (midline of frontal pole), Cz (midline of central pole), Pz (midline of parietal pole) and Oz (midline of occipital pole). The distance between Oz and the external occipital trochanter is 10%. The location of T3 (left middle temporal) electrode is 10% of the connecting line between the anterior fovea of both ears and the anterior fovea of the left ear. After that, an electrode is placed every 20% to the right, which is C3 (left center), Cz, C4 (right center) and T4 (right middle temporal). The distance between T4 and the anterior fovea of the right ear is

10%.FP1 (left frontal pole) is placed 10% to the left from FPz, and an electrode is placed every 20% from FP1 backward, which is F7 (left anterior temporal), T3 (left middle temporal), T5 (left posterior temporal) and O1 (left occipital). T3 is the intersection of this line and the connecting line of the anterior concave of both ears, and O1 is 10% from oz; Corresponding to this, the right temporal is FP2 (right temporal pole), F8 (right anterior temporal), T4 (right middle temporal), T6 (right posterior temporal) and O2 (right occipital) from front to back.Each electrode is equipped with a data transmission chip. The chip reduces the scalp resistance through medical conductive paste. The EEG signal is transmitted to the amplifier through the chip to complete signal amplification, and then transmitted to the data acquisition system. Finally, the real-time data transmission with the host is completed.

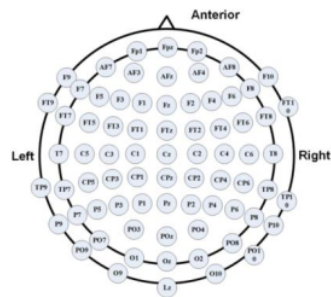


Figure 4 10-20 distribution of international brain electrical leads

5. Data analysis

Data processing and analysis of the data obtained from the test are mainly divided into three parts. The first part is to compare and analyze the energy spectrum of the noise samples of the test vehicle under different working conditions, and discuss the changes of the sound spectrum under different orders, different pedal openings and whether ASD mode is applied; The second part is based on the objective evaluation model to explore the linear relationship between subjective scoring and objective parameters; The last part is to visualize the results after a series of processing of EEG signals, explore their feature relationships with EEG topographic maps, and verify the feasibility of using them as acoustic quality evaluation indicators.

5.1 analysis of sample working conditions of standard vehicle noise

5.1.1 fixed gear order and variable gear order

Fig. 5 shows the energy spectrum diagram of the test vehicle logo 4008 under the three gear full throttle acceleration condition (WOT) in the ASD on mode. It can be seen that the order 2, 3.5, 4, 4.5, 5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5 and 10 of the vehicle noise orders of this model are prominent. Among them, orders 2, 4 and 6 are the main orders of the four cylinder engine, which have obvious order characteristics in the full speed range, so the subsequent data analysis mainly focuses on orders 2, 4 and 6.

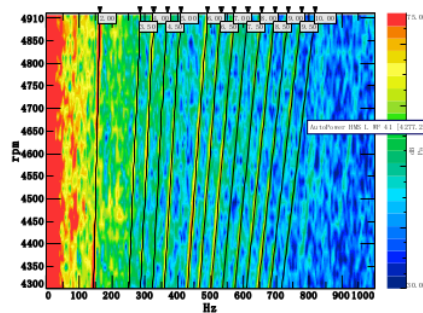


Figure 5 spectrum diagram of mark 4008 ASD on mode three gear full throttle acceleration working condition

Fig. 6 and Fig. 7 show the energy ratio of the main order of the test vehicle

mark 4008 under the three speed wot working condition of automatic gear and fixed gear in ASD on mode. The figure compares the energy ratio of the main order (2nd, 4th and 6th) of the sound collected by the forward ASD speaker of the mark 4008 under the working condition of the third gear of the positioning gear with the energy ratio of the main order (2nd, 4th and 6th) of the sound collected by the forward ASD speaker of the mark 4008 under the working condition of the automatic gear. It can be seen that the fixed gear and the automatic gear differ greatly in the energy ratio of the main order, and the change trend with the rotation speed is similar, but the energy is very different; And the energy ratio of the fixed gear in different main orders and the automatic gear in different main orders is also different. Therefore, it can be reflected that the energy ratio and the trend with the change of the speed of the vehicle noise in different orders of the same gear are very different, and different gears have a certain impact on the energy ratio of the vehicle noise.

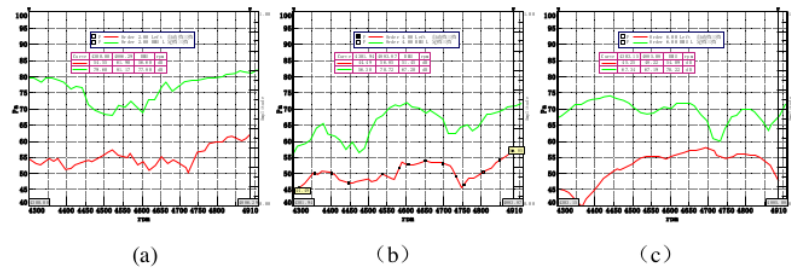


Figure 6 Comparison between 4008 ASD on mode automatic gear and fixed gear three gear wot mode: (a) 2nd order (b) 4th order (c) 6th order

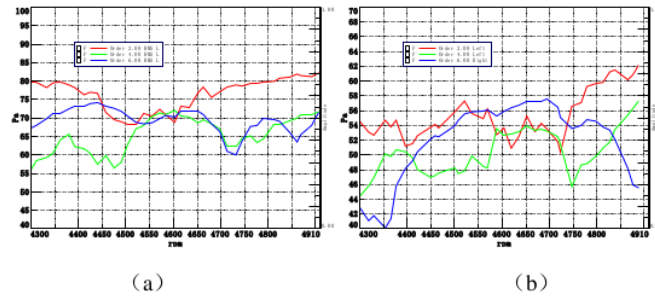


Figure 7 energy comparison of three main steps of marked 4008 ASD on mode: (a) fixed gear (b) automatic gear

Fig. 8 shows the energy spectrum diagram of the test vehicle BMW I8 under the three gear wot working condition in ASD on mode. It can be seen that under the

three gear wot working condition of BMW I8, the vehicle noise of this model is more prominent at steps 1.5, 2.5, 3, 3.5, 4.5, 5, 5.5 and 6. Among them, orders 1.5, 3 and 6 are the main orders of the three cylinder engine, which have obvious order characteristics in the full speed range. Therefore, the subsequent data analysis mainly focuses on orders 1.5, 3 and 6.

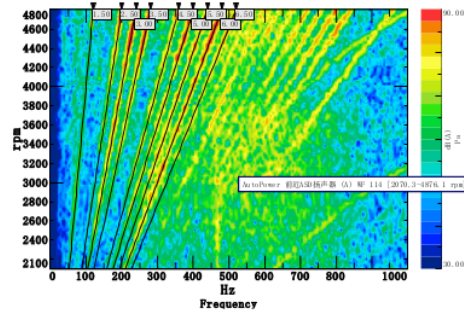


Figure 8 energy diagram of BMW I8 ASD on mode (three gear wot mode)

Fig. 9 is the energy ratio of the main order of the test vehicle BMW I8 under the three speed wot working condition of automatic gear and fixed gear in ASD on mode. The figure compares the energy ratio of the main order of the sound collected by the forward ASD speaker of the BMW I8 under the working conditions of the fixed gear and the third gear, that is, the energy ratio of the first order, the third order and the sixth order, and the energy ratio of the main order of the sound collected by the forward ASD speaker of the BMW I8 under the working conditions of the automatic gear and the third gear. It can be seen that when the rotation speed is greater than 4875r / min, the two lines roughly coincide, and the difference between the fixed gear and the automatic gear in the main order energy ratio is very small, and the overall change trend is roughly the same. However, for different orders of noise, the trend of the energy ratio changing with the rotation speed is different. When the rotational speed order is 1.5, the noise pressure level fluctuates with the increase of rotational speed, and shows a slightly decreasing trend as a whole; When the rotational speed order is 3, the sound pressure level of the rotational speed generally shows a slightly increasing trend with the increase of the rotational speed, and a trough value of the sound pressure level appears at the rotational speed of 5400 R / min; When the rotational speed order is 6, the noise sound pressure level fluctuates with the increase of rotational speed, and shows a slightly decreasing trend as a

whole. There are certain differences in the noise energy ratio of BMW I8 vehicles under different orders.

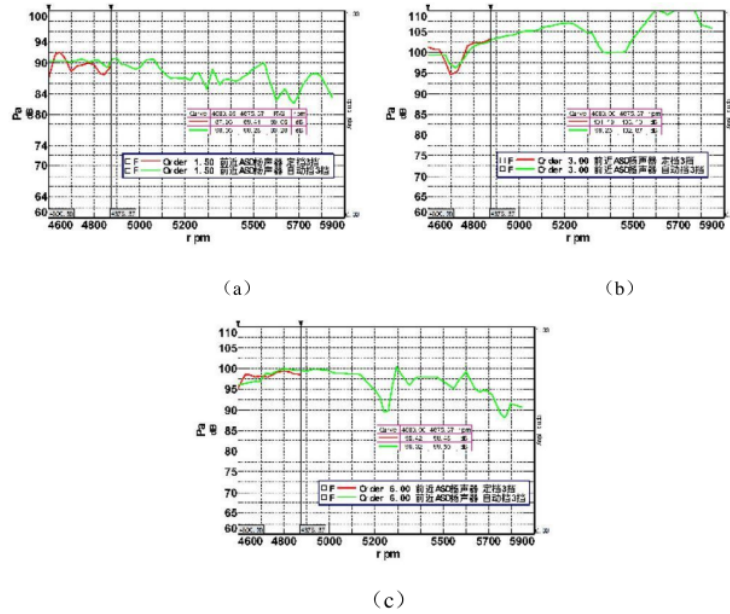


Figure 9 Comparison of energy between fixed gear and automatic gear main order of BMW I8 ASD on mode: (a) 1.5th order (b) 3rd order (c) 6th order

Fig. 10 shows the energy spectrum of the test car Audi R8 under the three gear wot working condition in the ASD on mode. In order to be consistent with the previous test vehicle data, the sports mode of Audi R8 is defined as ASD on, and the normal mode of R8 is defined as ASD off. It can be seen that under the wot working condition of three gears, the steps 1, 1.5, 2, 2.5, 3, 4, 4.5, 5, 5.5, 6 and 8 of Audi R8 are prominent. Among them, 2, 4, 6 and 8 have obvious order characteristics in the full speed range, so the subsequent data analysis mainly focuses on 2, 4, 6 and 8 orders.

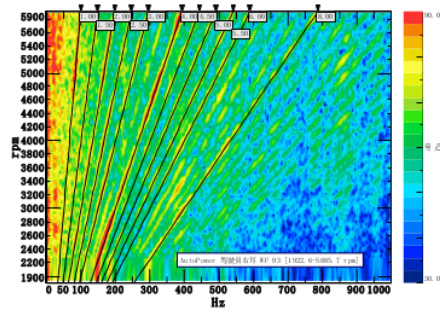
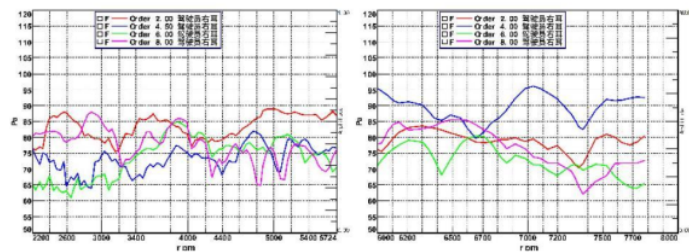


Figure 10 energy diagram of Audi R8 ASD on mode (three gear wot mode)

Fig. 11 and Fig. 12 show the energy ratio of the main order and the energy ratio of each order in different gears of the test car Audi R8 under the three gear wot working condition of automatic gear and fixed gear in ASD on mode. The two figures in Fig. 9 compare the energy ratio of the main order of the sound collected by Audi R8 under the three gear working conditions of automatic gear and positioning gear, that is, the second order, the fourth order, the sixth order and the eighth order. From the comparison chart, it can be seen that there is a big difference in the energy ratio of the main order between fixed gear and automatic gear. For the noise of different orders in the same gear, the trend of change with speed is also very different, but the overall fluctuation range is certain, And the noise energy ratio difference between the automatic gear and the fixed gear is larger. Fig. 10 describes the energy ratio of each gear of each main order, that is, gear 3, gear 4, gear 5 and gear 6, under the working condition of positioning gear. It can be seen from the comparison between gears that, in different gears, the energy difference of orders 4, 6 and 8 is small except for order 2, and the energy fluctuation of order 2 noise varies frequently with the speed. The change of different gears has little effect on the noise energy ratio of Audi R8, but different orders have a greater effect on the noise energy ratio of Audi R8.



(a)

(b)

Figure 11 main order energy ratio of Audi R8 ASD on mode automatic gear and fixed gear: (a) fixed gear (b) automatic gear

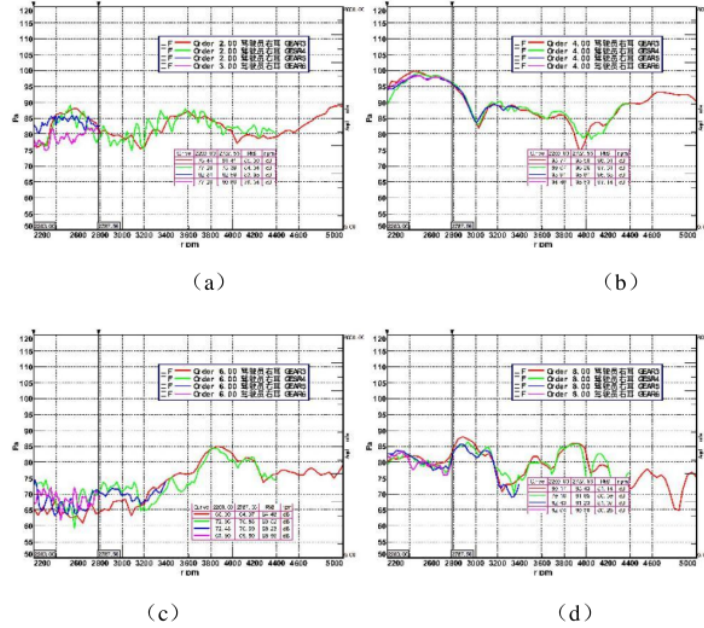


Figure 12 comparison between Audi R8 ASD on mode gears: (a) 2nd order (b) 4th order (c) 6th order (d) 8th order

5.1.2 Pedal gain

The RMS values and relevant data corresponding to the different speed ranges of the main orders of the test vehicles of various models under different opening pedal gains were recorded and analyzed in the experimental test. The test vehicle with pedal opening of 25%, 50%, 75% and wot mode was tested in the experiment. The energy ratio corresponding to different speed intervals was recorded every 200 R / min from 2150 R / min to 4250 R / min and described with a line graph.

Fig. 13 shows the change of the energy ratio with the rotation speed of the mark 4008 in the ASD on mode under the three speed wot working condition and the pedal opening of 25%, 50% and 75% respectively. The four color curves in each figure respectively represent the changes of pedal gain data in each speed range caused by different pedal opening under the 2nd, 4th and 6th working conditions. It

can be seen that the data of the mark 4008 under the wot working condition of the third gear is slightly similar to the data under the pot working condition of 25%, 50% and 75% pedal opening, but there is no overlapping section. Compared with the data under the condition that the pedal opening of the sign 4008 is 25%, the noise pressure level under the condition that the pedal opening is 50% and 75% is closer to the sound pressure level under the wot condition. The noise energy ratio with small pedal opening is different from that with large pedal opening.

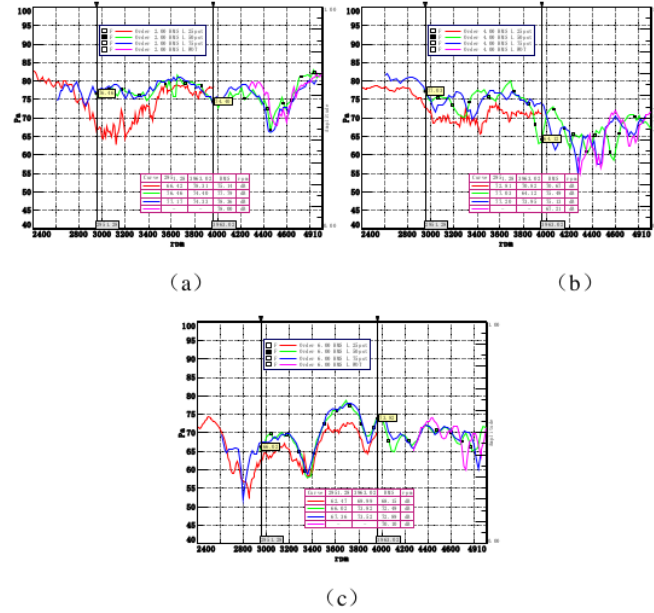


Figure 13 marks 4008 ASD on mode 3rd gear pedal gain: (a) 2nd order (b) 4th order (c) 6th order

Fig. 14 shows the change of the noise energy ratio with the rotation speed of the BMW I8 in the ASD on mode under the three speed wot working condition and the pedal opening of 25%, 50% and 75% respectively. The four color curves in each figure respectively represent the changes of pedal gain data in each speed range caused by different pedal opening under the working conditions of 1.5, 3 and 6 steps. It can be seen that the data of the BMW I8 under the third gear wot working condition and the data under the pedal opening 25%, 50% and 75% pot working conditions are almost the same in the third and sixth working conditions, while the data under the first and fifth working conditions are quite different, especially when the speed is less than 3500r / min. there is no overlap section. When the speed is

greater than 3500r / min, the fluctuation range decreases, but the change of energy ratio under different pedal opening is still different.

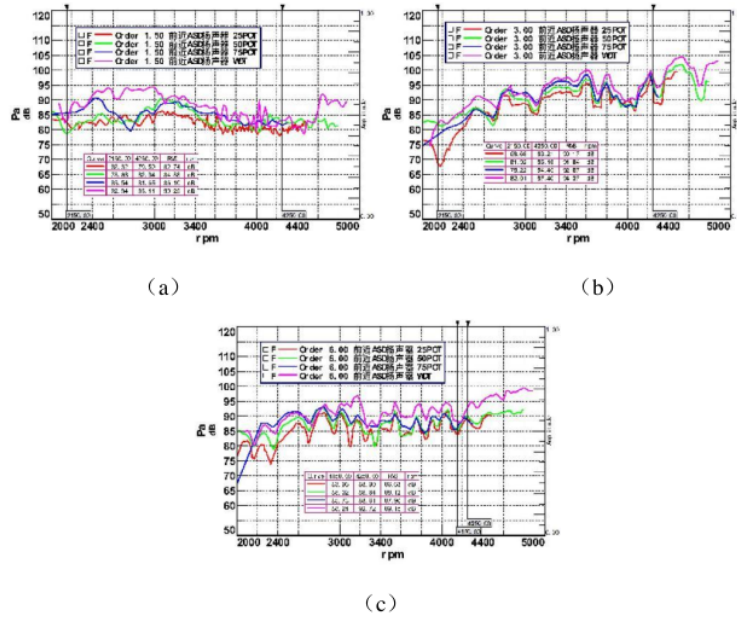


Figure 14 BMW I8 ASD on mode 3-step pedal gain: (a) 1.5th order (b) 3rd order (c) 6th order

Fig. 15 shows the change of the noise energy ratio with the rotation speed of Audi R8 in ASD on mode under the three speed wot working condition and the pedal opening of 25%, 50% and 75% pot working condition respectively. The four color curves in each figure respectively represent the changes of pedal gain data in each speed range caused by different pedal opening under the 2nd, 4th, 6th and 8th working conditions. It can be seen that the data of Audi R8 under the three gear wot working condition is quite different from the data under the pedal opening 25%, 50% and 75% pot working conditions. There is no overlap section, and the data fluctuates greatly with the increase of the speed. In particular, the noise energy ratio at the 4th and 8th stages fluctuates greatly with the pedal opening and speed. The change of pedal opening has a great influence on the noise energy ratio of Audi R8.

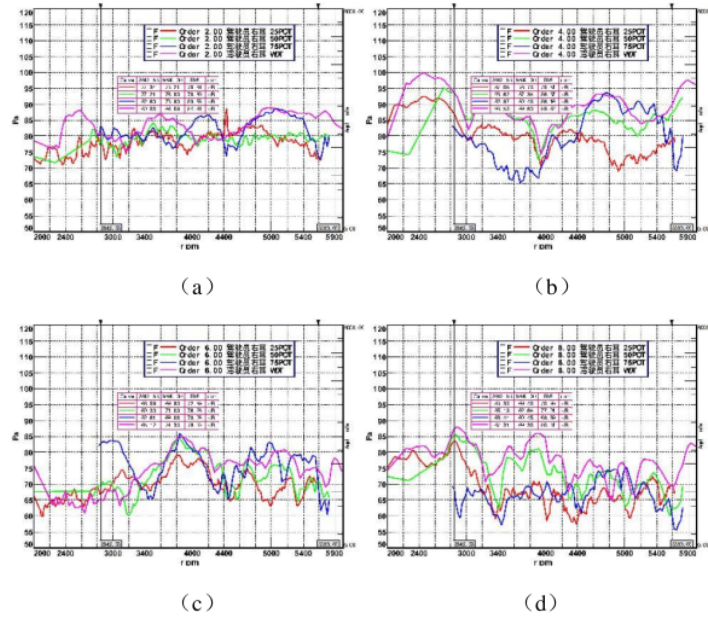


Figure 15 Audi R8 ASD on mode 3-step pedal gain: (a) 2nd step (b) 4th step (c) 6th step (d) 8th step

5.1.3 ASD switch mode difference

Analyze the comparison of working conditions of the test vehicle under ASD switch mode, mainly collecting the data of ASD on mode and off mode of the three types of test vehicles under the same working conditions through real vehicle test and processing and comparison. In the ASD off mode data, the data under 75% pot working condition of the third gear is too short, and the extracted speed is not ideal. Therefore, the data under 70% pot working condition is used to compare the difference between ASD on and off.

FIG. 16 shows the energy spectrum diagram of the ASD on mode and off mode of the marker 4008 under the third gear 70% pot working condition. 2. Orders 4 and 6 are the main orders of the four cylinder engine, which have obvious order characteristics in the full speed range. The data analysis mainly focuses on orders 2, 4 and 6. The energy of the test vehicle in the ASD on mode is higher than that in the ASD off mode. Fig. 17 is a comparison of the working conditions of the ASD switch mode of each main order of the mark 4008 under the three gear 70% pot working

condition. The curves in different colors represent the working condition changes of the ASD on mode and the ASD off mode respectively. It can be seen that the sound pressure level in the ASD on mode is always higher than that in the ASD off mode in the full speed range under a certain working condition of the test vehicle gear. ASD switch mode has a great influence on model 4008.

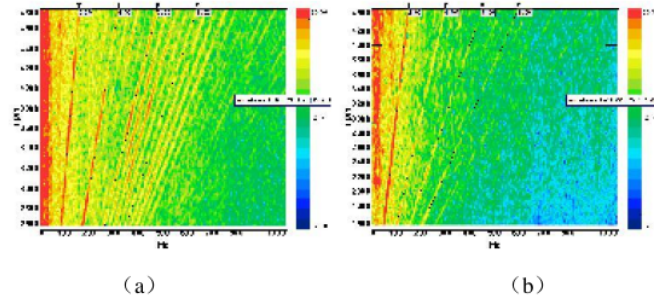


Figure 16 marks the difference of 70% pot ASD switch modes of 4008 three gears: (a) ASD on mode (b) ASD off mode

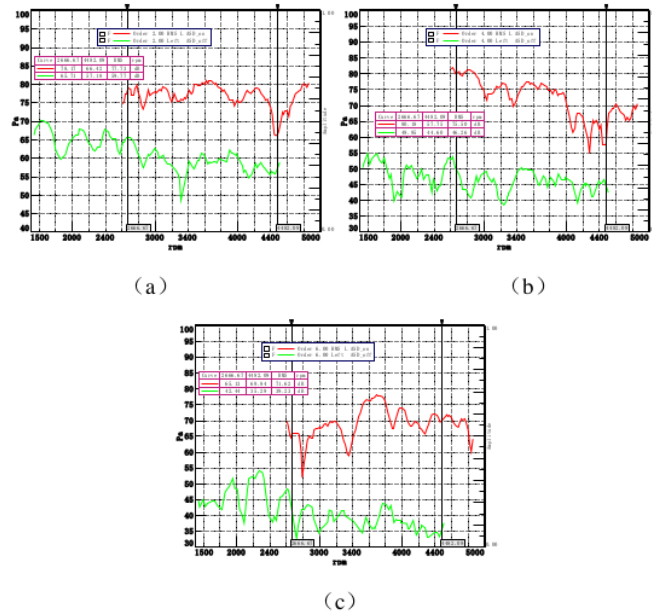


Figure 17 marks the differences of ASD switching modes of different orders of 4008 third gear 70% pot: (a) 2nd order (b) 4th order (c) 6th order

Fig. 18 shows the energy spectrum of the BMW I8 in the ASD on mode and off mode under the third gear 75% pot working condition. The ASD off mode of the BMW I8 can not lock the gear, so the time-domain information within the fixed gear

range can only be intercepted under the full working condition of 75% opening automatic gear. Find the corresponding gear data according to the speed or vehicle speed information after interception. Orders 1.5, 3 and 6 are the main orders, which have obvious order characteristics in the full speed range. Data analysis mainly focuses on orders 1.5, 3 and 6. The energy of the test vehicle in the ASD on mode is higher than that in the ASD off mode. Fig. 19 is a comparison of the working conditions of the BMW I8 in the ASD switch mode of each main order under the three gear 75% pot working condition, showing the changes of working conditions in the ASD on and off modes respectively. It can be seen that under the condition that the gear condition of the test vehicle is constant, the energy value in the ASD on mode is lower than that in the ASD off mode at the 1st and 5th steps, and the energy value in the ASD on mode is higher than that in the ASD off mode at the 3rd and 6th steps. ASD on / off mode has certain influence on the noise energy of BMW I8.

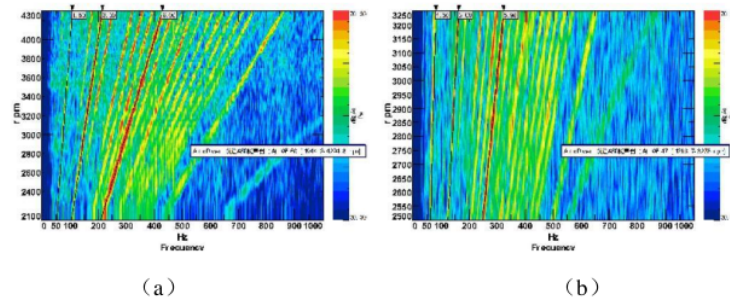
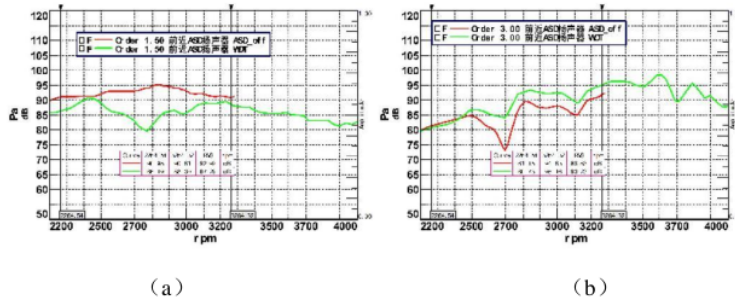
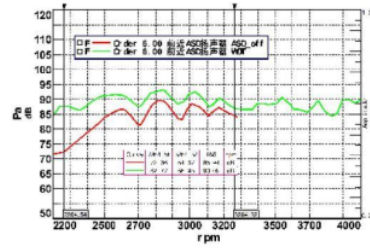


Figure 18 differences of 75% pot ASD switch modes in three gears of BMW I8: (a) ASD on mode (b) ASD off mode

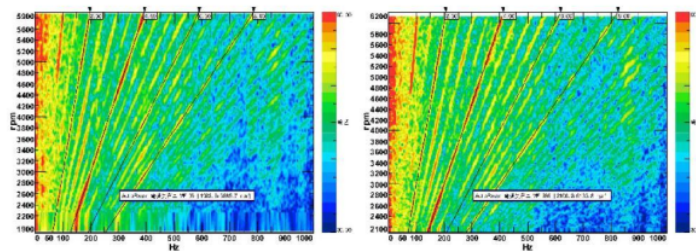




(c)

Figure 19 differences of ASD switching modes of 75% pot in the third gear of BMW I8 in different orders: (a) 1.5th order (b) 3rd order (c) 6th order

Fig. 18 shows the energy spectrum diagram of ASD on mode and off mode of Audi R8 under three gear 75% pot working condition. 2. Orders 4, 6 and 8 are the main orders, which have obvious order characteristics in the whole speed range. The data analysis mainly focuses on orders 2, 4, 6 and 8. Fig. 19 is a comparison of ASD switch mode working conditions of various main orders of Audi R8 under three gear 75% pot working conditions. From the energy difference data of main orders under different modes, it can be seen that there is little difference between R8's sports mode and ordinary mode. The noise energy ratio of different modes in each order has a similar trend with the rotation speed. ASD on / off mode has little influence on the noise energy of Audi R8.



(a)

(b)

Figure 20 difference of 75% pot ASD switch modes of Audi R8 three gears: (a) ASD on mode (b) ASD off mode

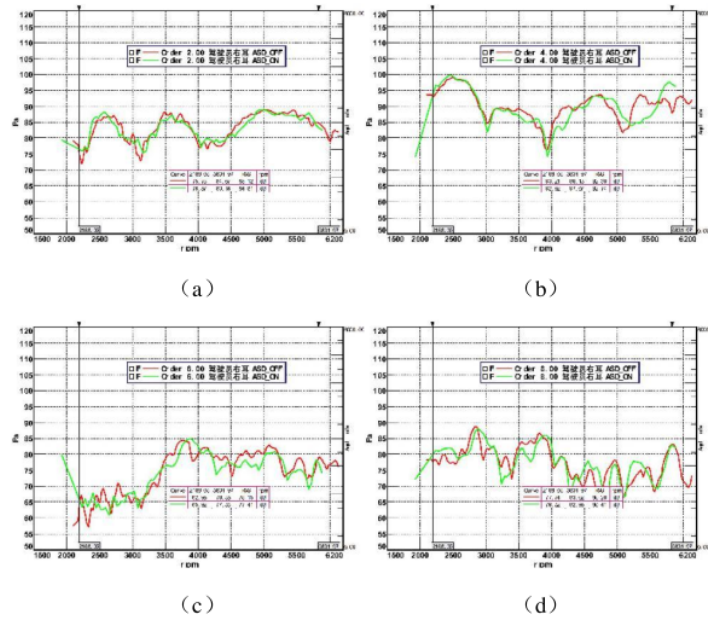


Figure 21 differences of ASD switch modes of different orders of Audi R8 third gear 75% pot: (a) 2nd order (b) 4th order (c) 6th order (d) 8th Order

5.2 analysis of subjective and objective evaluation results of sound quality

SPSS software is used to establish a subjective and objective evaluation model based on multiple linear regression. The dependent variable is the subjective evaluation value of the evaluator, and the independent variable is the objective parameter calculated in Table 3:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \varepsilon \quad (1)$$

Where: X_1 is loudness; X_2 is linearity; X_3 is volatility; X_4 is mi index; X_5 is bi index; X_6 is AI index; X_7 is sharpness; X_8 is roughness.

The subjective evaluation values and objective parameter values of 24 sound samples are input into SPSS software to establish an eight element linear regression model. Now the model summary and regression coefficients are listed, as shown in Table 3 and table 4.

Table 4 shows the fitting of the model. It can be seen from the table that the

complex correlation coefficient (R) of the model is 0.957, the judgment coefficient (R-square) is 0.916, and the adjusted judgment coefficient is 0.871, which indicates that the fitting degree of the model is good. From table 5, the linear regression equation of the subjective and objective evaluation of noise samples can be obtained as follows:

$$Y=21.393-0.049X_1-0.114X_2-13.490X_3-43.098X_4+0.114X_5-0.143X_6-13.863X_7-0.817X_8 \quad (2)$$

The constant term in the equation is 21.393, and the partial regression coefficient $\beta_1, \beta_2, \dots, \beta_8$ as shown in the above formula, after t-test, the significance test results of the other seven objective parameters except roughness show $P < 0.05$, indicating that the linear regression equation is significant, that is, the seven objective parameter variables have a significant linear impact on the subjective evaluation. Loudness has a significant negative impact on subjective score, and the higher the loudness, the lower the subjective score; The linearity has a significant negative impact on the subjective score, and the greater the linearity, the lower the subjective score; Volatility has a significant negative impact on subjective score, and the greater the volatility, the lower the subjective score; Mi index has a significant negative impact on subjective score. The larger the MI index, the lower the subjective score; Bi index has a significant positive impact on subjective score. The larger the Bi index, the higher the subjective score; The sharpness has a significant negative impact on the subjective score. The higher the sharpness, the lower the subjective score.

Table 3 model summary

Model	R	R side	R after adjustment	Error in standard estimation
1	0.957 ^a	0.916	0.871	0.085456560

Table 4 regression coefficient

parameter	Regression coefficient analysis				
	Regression coefficient	Standard error	Normalization coefficient beta	T test results	T-test significance

constant	21.393	3.107		6.885	0.000
loudness	-0.049	0.013	-2.470	-3.725	0.002
Linearity	-0.114	0.016	-0.802	-6.945	0.000
Volatility	-13.490	1.999	-1.494	-6.750	0.000
MI index	-43.098	12.959	-0.393	-3.326	0.005
BI index	0.114	0.022	1.423	5.207	0.000
AI index (%)	-0.143	0.029	-4.858	-4.941	0.000
Sharpness	-13.863	1.632	-3.132	-8.493	0.000
Roughness	-0.817	0.661	-0.277	-1.236	0.235

5.3 EEG data analysis

Because of the instability and irregularity of EEG signals, the data analysis of EEG signals is relatively complex, and it is difficult to directly analyze the corresponding laws from the original signals. Generally, the signal needs to be preprocessed to improve the signal-to-noise ratio of the signal to a certain extent, so as to obtain a signal with certain regularity, which is convenient for subsequent research. The data preprocessing in this paper is based on the eeglab.v2019.1 toolkit of MATLAB platform. This toolkit is mainly used for EEG signal analysis, which can filter, downsampling, time-domain and frequency-domain analysis, visual analysis, etc. The Toolkit provides edf, bdf, vhdr and other data formats. The EEG signals collected in this paper are in vhdr format, so the data preprocessing in this paper is based on eeglab toolkit.

The preprocessing steps of EEG signals include: locating electrodes, removing useless electrodes, filtering, downsampling, baseline correction, interpolation of bad leads, line noise elimination, bad channel processing, removing artifacts, re referencing, etc.

After the EEG data preprocessing, the next step is feature extraction. How to extract the most effective potential features for classification and recognition from the original data, so as to achieve data dimension compression, that is, to obtain a group of "few but fine" classification features with small classification errors. As a kind of nonlinear physiological signal with high dimension and high time resolution,

EEG usually needs to complete feature calculation from various angles, obtain feature matrix sets, and finally achieve high-efficiency classification. Feature extraction generally includes the extraction of time-domain features, frequency-domain features, time-frequency domain features, and spatial domain features. This paper mainly focuses on the first two aspects. In order to better display the feature extraction results, the EEG features are drawn into the EEG topographic map, which is implemented using MATLAB programming. Similar results were obtained after EEG data processing of different subjects. The following shows the EEG data processing and analysis of a certain subject.

Fig. 22 shows the time domain feature results of EEG signals. Fig. 22 (a) shows the spectrum diagram of brain energy changes and fluctuations with time, and Fig. 22 (b) shows the specific changes and distribution of EEG energy spectrum in different time periods. It can be seen that when stimulated by sound, the brain needs a short period of stress, and then the EEG energy will rise abruptly in a very short time, reach the peak after 200ms, then drop sharply, and then recover after a period of fluctuation. When the EEG energy is at the peak stage, it is the frontal page of the EEG that first changes dramatically, with the maximum energy, and then this change spreads to other parts. The changes of EEG energy are not necessarily symmetrical in electrode distribution.

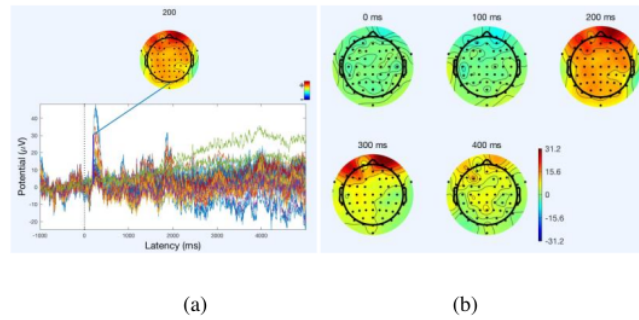


Figure 22 time domain characteristic results of EEG signal

Fig. 23 shows the frequency domain feature results of EEG signals. It can be seen from the figure that the energy at different electrode positions is different at different frequencies. With the increase of frequency, the EEG energy shows a downward trend as a whole. In the frequency range of 10-15hz, the energy fluctuates, rises briefly, reaches a local peak, and then decreases again. When the frequency is

6Hz, the maximum energy occurs in the frontal area; When the frequency is 10Hz, the maximum energy occurs in the occipital region; When the frequency is 22Hz, the energy distribution is relatively uniform, and there is large energy at the frontal, occipital and left and right ear electrodes.

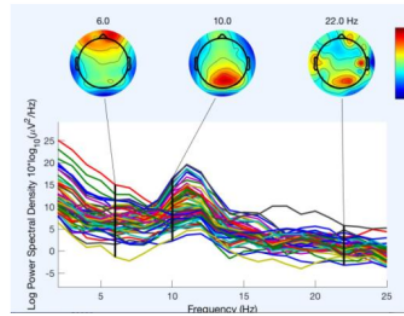


Fig. 23 frequency domain characteristic results of EEG signals

6. Results and discussion

6.1 Sound quality evaluation

The following results can be obtained by analyzing the real vehicle test conditions of three vehicles with different models applied with ASD technology, namely, Peugeot 4008, BMW I8 and Audi R8:

- The order characteristics have a great impact on the sound quality, especially the main order, which has obvious order characteristics in the full speed range. The fixed gear and the automatic gear of the mark 4008 differ greatly in the energy ratio of the main order, and the energy ratio of the fixed gear and the automatic gear at different main orders also differ greatly; BMW I8 fixed gear and automatic gear have almost no difference in the main order energy ratio; Audi R8 fixed gear and automatic gear differ greatly in the energy ratio of the main order, and in different gears, except for the second order, the energy difference of the fourth, sixth and eighth orders is small.
- Pedal opening has a certain impact on vehicle noise energy ratio. Compared with the data under the condition that the pedal opening is 25%, the energy value under the condition that the pedal opening is 50% and 75% is closer to the energy value under the wot condition; The data of the BMW I8 under the third wot working condition and the data under the pedal opening 25%, 50% and 75% pot working conditions are almost the same under the third and sixth working conditions, while the data under the first and fifth working conditions are quite different; There is no overlap between the data of Audi R8 under three gear wot working condition and the data of pedal opening under 25%, 50% and 75% pot working condition, and the data fluctuates greatly with the increase of speed.
- The influence of ASD switch mode difference on vehicle noise condition depends on vehicle model. The energy ratio of the logo 4008 and the BMW I8 in the ASD on mode is always higher than that in the ASD off mode; The sports mode of Audi R8 is not different from the normal mode.

This paper also calculates the subjective evaluation score and psychoacoustic objective parameters based on the car noise sound samples, and mainly selects eight commonly used objective parameters. A multiple linear regression model of subjective and objective evaluation is established, and the model has a good fitting degree. The results show that the increase of loudness, linearity, volatility, roughness, AI index and sharpness has a negative impact on subjective perception, and the increase of Bi index has a positive impact on subjective perception.

In addition, through the processing and analysis of EEG data, that is, the data preprocessing and the extraction of time-domain and frequency-domain features, it is found that the energy of EEG signals also changes when the time and frequency-domain conditions change, and its trend is shown in the form of EEG topographic map, which proves the feasibility of EEG signal recognition of sound quality.

6.2 Target sound design

The vehicle active sound design is proposed to meet the needs and pleasant experiences of drivers and passengers for the sound interest during the driving process through active sound generation, and to improve the safety of driving outside the vehicle. Therefore, the car sound effect feeling expected by drivers and passengers, that is, the subjective feeling of drivers and passengers about the car sound, plays an important guiding role in the control strategy and function development of the active sound design system of cars. It can also be seen from the above that there is a link between subjective feelings and objective parameters of automobile sound quality. A standardized evaluation model can be established through the correlation between psychoacoustic parameters and subjective evaluation results of sound quality to objectively quantify Abstract sound quality.

The design process of the target sound mainly includes: (1) through questionnaire and other methods, we can understand the sound effect needs and preferences of users, and determine the design direction and goal of the sound; (2) The sound sample library can be constructed by collecting noise signals of different vehicle models, obtaining relevant network sound resources, synthesizing sound based on visualization software, etc; (3) Debug and evaluate the sound,

quantitatively analyze the sound quality objectives according to the subjective and objective evaluation model, including frequency equalization, order distribution and various psychoacoustic objective parameters, evaluate and select a large number of sound effect samples, modulate the sound, and then evaluate the modulated sound subjectively and objectively to judge its consistency, The design and modulation of sound is a process of repeated iteration and screening; (4) Sound synthesis is realized through harmonic synthesis, particle synthesis and other methods, and real vehicle loading and verification are carried out. The speed of the power source and the opening of the accelerator pedal are the two most important indicators for controlling and sensing the operating state of the vehicle. The active sound design simulates the engine sound in real time according to these two indicators. For different vehicle driving conditions, different sound synthesis and decomposition algorithms are used to synthesize the target sound samples. Finally, the NVH performance of the sample vehicle is tested and evaluated to determine whether it meets the design requirements of the target sound.

7. Conclusions and recommendations

In this paper, three different models of cars with ASD technology, i.e. Peugeot 4008, BMW I8 and Audi R8, were tested and analyzed. The research shows that the ASD mode of different models of cars has different effects on their noise, and the order characteristics and pedal opening will also affect their sound quality. The order characteristics have a great influence on the sound quality, especially the main order, which has obvious order characteristics in the whole speed range. Pedal opening has a certain effect on the energy ratio of vehicle noise. The influence of ASD switch mode difference on vehicle noise condition depends on vehicle model. Then, the car noise samples measured in the experiment were scored by subjective evaluation and the psychoacoustic objective parameters were calculated. Eight commonly used objective parameters were mainly selected: loudness, sharpness, roughness, AI index, Bi index, MI index, volatility and linearity. A multiple linear regression model for subjective and objective evaluation is established. The model has a good fitting degree. Except for roughness, the other seven objective parameters have a significant linear impact on subjective evaluation, and a linear regression equation based on these parameters is given. The target sound can be designed according to these results, so as to meet the needs of drivers and passengers for the interesting sound and pleasant experience during the driving process of the vehicle, as well as the safety requirements for driving outside the vehicle. This paper proposes the design steps and methods for the target sound with specific requirements. In addition, the feasibility of evaluating sound quality with EEG signals is proved by processing and analyzing EEG signals under sound stimulation.

There are also some deficiencies and room for improvement in this study. The first part is about the processing and analysis of EEG signals under sound stimulation. This paper only completes the separate processing of single data. In order to better verify the conclusion, all data should be processed and analyzed in batches. In the EEG data processing part, we mainly use the eeglab toolbox and MATLAB programming in MATLAB. We can also explore more applicable EEG analysis toolkits and more optimized and concise code programming. In the EEG feature extraction part, we can try to use deep learning algorithms such as random forest, support vector machine or neural network algorithms for feature extraction

and classification, which can improve efficiency and accuracy compared with manual feature extraction. Finally, in the sound design part, only the design process and method are proposed, and its practice part has not been implemented, which needs further exploration. Due to the limitations of the initial exploration and experimental conditions, there are still many shortcomings in the research work, which need to be improved and perfected one by one in the future research, which points out the direction for the next research, with a view to further research and exploration.

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Appendix

1.timetable

ID	task	Start time	End time	timescale	Task Completion	2022-05-01					2022-09-01	2022-10-01
						2022-05-01	2022-06-01	2022-07-01	2022-08-01	2022-09-01		
1	Literature research	2022-04-29	2022-05-28	30.0 日	100.0%							
2	Determination and preparation of research plan	2022-05-20	2022-06-18	30.0 日	100.0%							
3	experiments	2022-06-18	2022-08-01	45.0 日	100.0%							
4	Data processing and analysis	2022-06-30	2022-08-13	45.0 日	100.0%							
5	Writing papers	2022-08-20	2022-09-06	18.0 日	100.0%							

Master's Project_Zihui XIAO(2106354)

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