

Article

Research on the Design Method of Pure Electric Vehicle Acceleration Motion Sense Sound Simulation System

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Abstract: Due to the emerging trend of energy conservation and emission reduction around the world, the new energy vehicle industry has achieved rapid development. However, there are new challenges regarding vehicle NVH (noise, vibration, and harshness). When a pure electric vehicle is being driven, the inside of the vehicle is relatively quiet, which cannot bring the driver sound feedback reflecting the change of the vehicle state. In order to solve this problem, this paper studies the design method of a sound simulation system for acceleration motion in pure electric vehicles. In this paper, the motion characteristics of automobile engine acceleration sound, sound signal analysis and processing, subjective evaluation of sound quality, and sound synthesis strategy are studied. By reading the vehicle running state data on the CAN bus of pure electric vehicles, the goal of engine motion sense sound simulation during vehicle acceleration is achieved. This helps to enhance driving feedback and improve user driving experience.

Keywords: electric vehicle; sound simulation system; NVH; design method



Citation: Fu, J.; Zhu, C.; Su, J. Research on the Design Method of Pure Electric Vehicle Acceleration Motion Sense Sound Simulation System. *Appl. Sci.* **2023**, *13*, 147. <https://doi.org/10.3390/app13010147>

Academic Editor: Edoardo Piana

Received: 27 October 2022

Revised: 13 December 2022

Accepted: 15 December 2022

Published: 22 December 2022



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1. Introduction

1.1. Research Status of Sound Simulation Systems

1.1.1. Sound Design and Simulation Technology

Many scholars have conducted relevant technical research on engine sound simulation systems. Initially, in 2001, Scott A and Amman et al. proposed voiceless and voiced sounds, which are similar to speech processing techniques. In this concept, the engine sound signal is decomposed into a deterministic component and random component; the deterministic component is extracted using a synchronous discrete Fourier transform method, and the stochastic component is modeled using a new multipulse excited time-series modeling technique, which will determine the components and random component in order to synthesize the engine sound signal [1–3]. Genuit et al. connected the sound samples sequentially and used this method to simulate and synthesize the sound of the engine so that it could vary with speed and load during simulation [4]. Van Rensburg et al. amplified or compressed the engine sound at different speeds by applying phase encoder technology to adjust the frequency of the sound signal, thereby simulating the engine sound of different states, but the relative amplitude of the sound harmonics is fixed. On this basis, Heitbrin measured the sound of the engine under different operating conditions and transposed and weighted it, correlating the relative amplitude of each harmonic of the sound with the engine speed [5,6]. Norio Kubo, a Japanese researcher, designed the engine sound using signal processing methods, using the active sound technology in the car of an electric vehicle to simulate the engine sound [7]. In 2012, Zhekova proposed a method to simulate the diesel engine idling sound by using Garber transform and time-frequency analysis for particle synthesis of diesel engine idling sound; however, this method is only applicable to diesel engine idling conditions and is not applicable in other operating conditions [8]. Based on the digital audio control algorithm, French technical researcher Patrick Boussard

et al. elaborated on the selection, comparison, and implementation of fitting parameters in active sound synthesis technology [9]. Jagla et al. proposed a method to simulate the sound at any engine speed by framing the sound samples into small fragments of milliseconds based on the principle of time-domain fundamental sound synchronization superposition technique in the field of speech synthesis, and by adaptively calculating and playing the sound fragments according to the change of engine excitation frequency [10]. Korean scholar Gwak studied sound design and subjective perception evaluation and concluded that when an electric vehicle accelerates, the sharp sensation of sound in the car decreases as the sound order in the low-frequency range increases [11]. Matthias Frank et al. studied the changes in the influence of spatial sound field distribution caused by speaker placements on the characteristic parameters of simulated sound; Simon Ahrens proposed that the audio system composed of in-car speakers can be used for the active management of sound, and the order components of the sound of the car engine can be modified appropriately to achieve the purpose of sound modification. Subsequently, David Welsh et al. used the car audio system to realize the sound simulation in the car and the warning sound prompt for pedestrians outside the car, and developed the acceleration sound with different auditory feelings according to the sound quality characteristics [12–14].

Regarding sound simulation system technology research, it has started a little late and mainly depends on research done in colleges and universities. The installation of a sound simulator was proposed by Wang Xiaoli and others to solve the problem of electric vehicles that were too quiet. She also studied how to use voice processing software and related hardware systems in pure electric vehicle sound simulations [15]. In the same year, an active sound management system was developed by Hu of Jilin University, which is used for sound simulation in the car and warning sound outside the car. The sound design, synthesis algorithm, and hardware implementation of the system are described in detail. Jia of Soochow University studied the engine sound simulation system used in hybrid vehicles where a good transition of sound was achieved during vehicle mode switching [16,17]. Huang of Southwest Jiaotong University proposed a method to realize driving motion in the study of vehicle driving simulators. This method combines the reading of different sound effects with the simulated driving platform [18]. Cao proposed a method of sound synthesis. This method is based on the short-time Fourier transform and synthesis technology of the Kaisai window function. The sound concept design goal in the car is formulated, and the sound calibration and evaluation method is established [19]. Zhu of Jiangnan University proposed a method for real-time synthesis of engine sound. This method is based on the continuous speed sample of the engine and extracts the harmonic parameters of the sound through discrete Fourier transform and K-means clustering. The mathematical model of the spectrum is established, and then the harmonic parameters are brought into the mathematical model. The sound of the corresponding engine speed is calculated in real time [20]. Cao of South China University of Technology studied how to design the electric car sound based on the needs of people; the sound pattern and type of sound quality perception is studied and a set of virtual reality car sound evaluation system was developed [21]. In addition, Pan Lei of SAIC Technology Center proposed a vehicle active sound control method. This method takes the vehicle operating parameters as the input and synthesizes based on the ‘particle algorithm’ extended by the overlapping addition algorithm. This method improves the interest of sound during driving and is verified by real vehicles [22]. The feature classification of the sound is used by Wang Weidong of the Pan-Asian Automotive Technology Center for active sound effect analysis. This technology has achieved good results through sound effect classification; therefore, this feature classification method can be applied to the sound design of new energy vehicles. Chen proposed a method where the engine exhaust sound can be analyzed offline and the corresponding segments are extracted; then, the motional exhaust sound is applied to the pure electric vehicle to simulate the acceleration sound [23,24].

Research by scholars on automobile sound simulation systems has mainly focused on the analysis of sound and sound synthesis technology. The sound quality of the auto-

mobile interior is directly affected by the auditory perception of simulated active sound. Automotive accelerated sound quality theory is used in sound design combined with sound synthesis technology to create a more personalized acceleration sound for pure electric vehicles.

1.1.2. Research on Accelerated Sound Quality Characteristics

The subjective feeling of car noise can be judged by car sound quality. Due to the structural characteristics of the electric drive system, the acceleration noise in a pure electric vehicle has been greatly reduced compared with a fuel vehicle. However, due to the lack of acceleration sound quality, it is still difficult for the driver to obtain a good acceleration driving experience. In the field of vehicle acceleration sound quality, great progress has been made after years of research by researchers at home and abroad, including the theoretical composition of acceleration sound quality and the subjective evaluation method of acceleration sound quality.

Solomon proposed the concept of the semantic segmentation method for sound quality evaluation, a relatively complete sound quality evaluation process, which was proposed after the improvement of the method [25]. Roland summarized the methods used in subjective and objective evaluation of sound quality and expounded the setting of sound quality goals and the realization process of sound quality [26]. The noise of motorcycles was modulated by Ming-Hung et al., and the sound quality goal of 'sporty feeling' was proposed, indicating that enhancing the specific order noise component is conducive to improving the 'sporty feeling' of sound [27]. Takao proposed that the sound quality in the car can be identified by two goals, namely 'comfortable sensation' and 'sporty feeling'. Different sound quality perceptions are related to their spectral composition and envelope [28]. Biermayer defined the subjective feeling of 'sporty feeling' as related to factors such as order components and tone [29]. Yasuo proposed that the sound quality of the interior acceleration 'sporty feeling' is affected by many factors, such as the main order, tone, and some parameters related to the speed. Therefore, the intake system of the car can be designed to achieve the 'sporty feeling' of the sound quality in the car [30]. Kousuke studied subjective evaluation models of sound quality perception in different countries and pointed out that people's perceptions of 'motion' and 'luxury' sounds were different in different countries [31]. Scholars have mostly studied the subjective evaluation and implementation methods of accelerated sound quality. The paired comparison method in subjective evaluation has been studied and improved by Mao, Jiao, and others. They mainly studied the influence of population classification on the evaluation results in the subjective evaluation test of sound quality. In order to improve the accuracy of the evaluation results, they evaluated the subjective preference of paired comparison through crowd classification, and then a triangular loop test algorithm was proposed to accurately calculate the misjudgment rate of the paired comparison method, and the empirical formula of the algorithm was derived [32–40]. The test method of vehicle sound quality was studied by Shen Zhe, and the evaluation process was explained. The influence of evaluation method and subjective evaluation group on the test results were compared [41].

Generally speaking, scholars describe the characteristics of accelerated sound quality through these subjective feeling words, including 'sense of movement', 'sense of pleasure', 'sense of comfort', 'sense of motivation', 'sense of luxury', 'sense of acceleration', 'sense of strength', 'sense of vitality', etc. Scholars' research on sound quality is mainly based on the existing evaluation methods, and the evaluation results are improved in terms of data screening, evaluation efficiency improvement, and stability maintenance.

1.2. Application Status of Sound Simulation System

The early sound simulation system was used in traditional fuel vehicles to enhance the sound of the engine. Even when driving a regular car, it can resemble the acceleration sound of a top sports car when accelerating. Volkswagen has installed an in-vehicle sound synthesis system on Golf, Suteng, Siborui, and other models to achieve the effect of dynamic

enhancement of vehicle driving sound. The artificially simulated sound is installed in the Audi A3 pure electric version of the car and played through the car audio system. Figure 1 shows a Volkswagen Golf with an acoustic wave augmentation system.



Figure 1. Volkswagen Golf with sound enhancement system.

The device that simulates the engine sound is installed on the electric version of Smart by Mercedes-Benz, which can achieve the same acceleration sound effect as the gasoline version of the vehicle. The electronic device, named ‘SLS cSound’, is installed in the subsequent pure electric version of the SLS AMG Coupe model, and different sound levels are set to output the driving sound matching the vehicle running state. The car engine sound simulation system is installed on some models of the BMW M series by BMW, named ‘Active Sound Design’ (ASD) system. The sound is played through the sound system in the car, and both the driver and the passenger can feel the strong acceleration sound wave in the car. After the eight-cylinder engine was replaced with a more fuel-efficient four-cylinder engine, Ford added a sound amplification system to the Mustang for sound enhancements based on the original vehicle’s accelerated sound. The sound simulation system is installed in the NX series of Lexus. In the motion mode, the vehicle can add additional sound to the original engine sound. The system will mix the two sounds in proportion and play the output through the sound system in the car. Traditional luxury car brands in the world have occupied a considerable market; almost all of their introduction of pure electric vehicles with the sound simulation function is to give users a better driving experience.

At present, the new energy automobile industry is developing rapidly, and some models have successfully applied the acceleration sound simulation technology of pure electric vehicles. For example, G3 released by Xiaopeng, an electric vehicle brand, has the function of simulating throttle acceleration roar. The Xiaopeng G3 car has set up four different gear acceleration sounds; the car acceleration sound mode can be manually selected by the user.

2. Sound Simulation System Design Methods

2.1. Target Sound Design Method

2.1.1. Engine Noise Production Mechanism

The sound of the engine is one of the main sources of noise when the car is running, and the main noise components are shown in Figure 2. Mechanical noise is caused by the inertial impact of the mechanical parts inside the engine during operation. Combustion noise is mainly generated by the sudden change of gas pressure produced inside the cylinder during ignition. These forces act on the engine block and cause the machine to vibrate and make noise. The aerodynamic noise is mainly produced by the intake and exhaust of the engine, and is dominated by the exhaust noise. They radiate directly into the air [42].

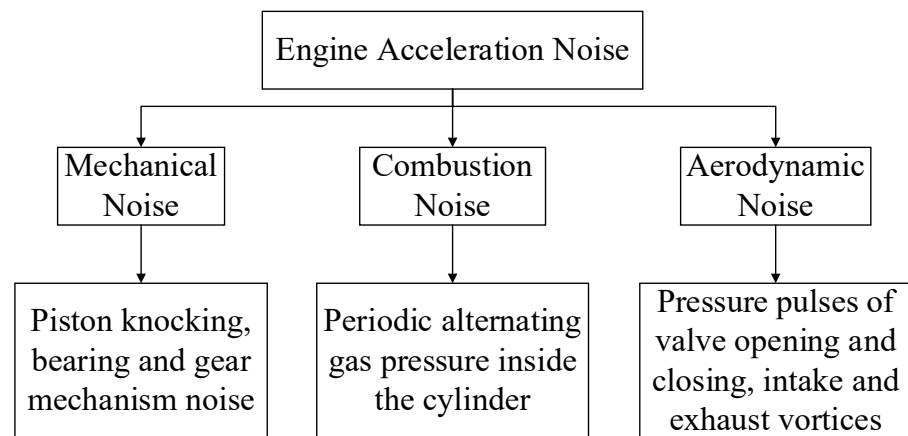


Figure 2. Main engine noise components.

Car acceleration process car in the car's main engine noise for the exhaust noise, and engine ignition do work combustion sequence, multi-cylinder engine according to the different working order for periodic ignition combustion.

In single-cylinder engines, the gas combustion in the cylinder exerts a force on the piston; its size is:

$$F_{zg} = (P - 1) \times A \quad (1)$$

In Equation (1), P is the burst pressure of the gas on the top surface of the piston, A is the surface area of the top of the piston, and F_{zg} is the main power acting on the engine crank linkage mechanism.

M_{xg} is the torque generated by gas combustion and the expression is as follows:

$$M_{xg} = F_{zg}r(\sin \alpha + \frac{\lambda}{2} \sin 2\alpha) = (P - 1)Ar(\sin \alpha + \frac{\lambda}{2} \sin 2\alpha) \quad (2)$$

Torque fluctuation of gas torque is influenced by the number of engine strokes; two-stroke engines have an operating cycle of 360° . The crankshaft rotates 360° for one cycle. In this case, the gas torque is only of integer order. The operating cycle of a four-stroke engine is 720° ; this means that for every 360° of crankshaft rotation, the engine goes through 0.5 cycles. Therefore, the torque fluctuation of a four-stroke engine contains an equal order component of 0.5 and 1.5 [43]. For a four-stroke engine, Equation (2) is expanded using the Fourier series to obtain the gas torque expression as:

$$M_{xg} = \overline{M}_x + a_{0.5} \sin(0.5\omega t + \varphi_{0.5}) + a_1 \sin(\omega t + \varphi_1) + a_{1.5} \sin(1.5\omega t + \varphi_{1.5}) + a_2 \sin(2\omega t + \varphi_2) \quad (3)$$

In Equation (1), M_{xg} is the effective output portion of the gas torque, $\overline{M}_x$ is the average torque, and a_i and φ_i are the amplitude and phase of each order of the gas torque fluctuation part, respectively. These gas torques are the source of engine order noise.

2.1.2. Engine Order Sound Mathematical Model

Taking the common four-stroke four-cylinder engine on the market today as an example, an engine's working cycle is intake, compression, work, and exhaust. There is one ignition for each cylinder during the complete cycle; the gases in the combustion chamber of the cylinder are ignited in a certain sequence and then a continuous ignition harmonic is formed. This is the main component of engine noise. The ignition frequency of the four-stroke engine sound is (4).

$$f_e = \frac{r}{60} \cdot \frac{n}{2} \quad (4)$$

In Equation (4), n is the number of engine cylinders, and r is the engine speed per minute. The harmonics corresponding to the fundamental frequency f_e are the main order of the engine sound.

In a four-cylinder engine, one rotation of the crankshaft will fire two cylinders, and only one combustion occurs in each cylinder during a complete working cycle. So, in addition to the main order, there are two harmonic orders (5) and (6).

$$f_o = \frac{r}{60} \quad (5)$$

$$f_h = \frac{1}{2} \cdot \frac{r}{60} \quad (6)$$

In Equation (1), f_o is the frequency corresponding to the engine speed. In Equation (1), f_h is the frequency corresponding to the complete working cycle of the engine. In a four-cylinder engine, these two frequencies correspond to the harmonics integer order harmonic and half order harmonic, respectively.

When the speed of the four-stroke engine is 3600 r/min, from the above equation, the corresponding firing frequency can be calculated. The firing frequencies of four-, six-, and eight-cylinder engines at this speed are 120 Hz, 180 Hz, and 240 Hz, respectively. Therefore, the firing frequency contribution of a cylinder is 30 Hz and the engine speed corresponds to a frequency of 60 Hz. Therefore, it can be calculated that the main order components of four-, six-, and eight-cylinder engines at this speed are 2nd, 3rd, and 4th order excitation, respectively. The firing frequency of engines with different cylinder numbers are contributed by the firing frequency of each cylinder. Thus, the 0.5 order is the minimum interval of engine order sound components.

When the engine speed is r , the 0.5th order sound component signal expression is (7).

$$\begin{aligned} x_{0.5}(r) &= A_{0.5} \sin(2\pi f_h + \varphi_{0.5}) \\ &= A_{0.5} \sin\left(\frac{\pi r}{60} + \varphi_{0.5}\right) \end{aligned} \quad (7)$$

In Equation (7), $A_{0.5}$ is the instantaneous amplitude of the 0.5 order engine sound, and $\varphi_{0.5}$ is the instantaneous phase of the 0.5 order engine sound. When the speed is r , the n th-order engine sound signal expression is (8).

$$\begin{aligned} x_n(r) &= A_n \sin(2\pi f_n + \varphi_n) \\ &= A_n \sin\left(\frac{\pi r}{60} \cdot n + \varphi_n\right) \end{aligned} \quad (8)$$

Then, the sound signal of the engine sound order in the car can be expressed as (9).

$$x(r) = \sum_{n=1}^N A_n \sin\left(\frac{\pi r}{60} \cdot n + \varphi_n\right) \quad (9)$$

2.1.3. Sound Target Setting in the Car

The difference in car acceleration sound gradually evolves into a driving experience that can bring the driver different characteristic styles. According to the spectral characteristics of acceleration sound, designing a recognizable acceleration driving sound is the main goal of car sound design.

Due to the human ear's ability to discriminate the characteristics of different sound sources and the subjective perception formed, in the long history of automotive development, people's auditory perception of the car engine sound can be described as comfort, sportiness, luxury, etc. This is a subjective preference of people for acceleration noise. For each major OEM, according to their own vehicle positioning differences, the sound quality in the car will also be tuned accordingly to meet the positioning requirements. Sound with a sense of acceleration and movement of the auditory sensation can most intuitively make the driver feel the dynamics of the car. Take advantage of the acceleration power of pure electric vehicles and use the 'sportiness' of the sound as a design goal for the

acceleration sound in pure electric vehicles. This enhances driving feedback and boosts driving excitement.

The “Sense of Movement of sound” can be described in two dimensions, namely subjective and objective. In the subjective hearing, the engine sound is bright and pleasant when accelerating and there is a clear roar that is rich, full, and rhythmic overall, providing a powerful experience. In objective terms, it is mainly manifested as a rich order component dominated by the ignition order and supplemented by the harmonic order, with a frequency concentration in the low frequency range of 0–1000 Hz. According to the existing studies on motion-sensitive sound quality, there are a series of subjective auditory descriptions of motion-sensitive sounds. Table 1 shows a description of motion-sensitive sounds.

Table 1. Description of motion-sensitive sounds.

Description Dimension	Related Semantics
Auditory characteristics	Thicker; a little roughness; low; full sound; clear; low-speed rumble; pure sound; intense sound; pitch undulation; pleasant
Driving Experience	Pleasant; kinetic; powerful; exciting; exhilarating; interesting; restless; urgent; strong driving sensation

2.2. Sound Synthesis Method

Sound Synthesis Algorithm Analysis

Currently, the main use of sound synthesis algorithms can be usually divided into two categories: parameter analysis and synthesis and time domain waveform synthesis, usually used in the field of speech synthesis. Parametric analysis synthesis is mainly based on the relevant sound channel model and calculates the corresponding sound parameters and sound synthesis. This method can greatly reduce the storage space for sound and has relatively flexible control of sound parameters to realize multiple variations of sound. It has been widely used in the field of speech synthesis. However, the sound synthesized by this method is rather stiff and lacks a sense of naturalness.

Time-domain waveform synthesis is the encoding and storage of sound sample waveforms. Alternatively, one can store the time domain waveform after editing the fragments according to the fundamental sound, and then synthesize the final speech after selecting and splicing the stored sound sample fragments and adjusting them according to external conditions. This method synthesizes speech based on the original sound fragments with more natural sound quality but requires more storage space for the sound fragment samples.

The number of primitives in engine sound is greatly reduced compared with speech which can effectively save storage space to make the simulated engine acceleration sound natural and harmonious. In this paper, we analyze the time-domain waveform synthesis method to synthesize sound based on the idea of synchronous superposition algorithm of time-domain fundamental tones.

In the process of implementing the time-domain fundamental sound synchronization superimposition algorithm for the engine acceleration sound, the sound signal needs to be framed to get a number of short time signals, with one primitive per frame as a sound sample. The period between primitives is then adjusted synchronously. Finally, we select the appropriate primitive fragment according to the external conditions to splice the synthesized sound [44,45].

The principle is essentially to use short-time Fourier changes to reconstruct the signal. For signal A , the short-time Fourier transform is (10).

$$X_n(e^{jw}) = \sum_{m=-\infty}^{+\infty} x(m)w(n-m)e^{-jwm} \quad (10)$$

In Equation (10), $n \in \mathbb{Z}$, $\mathbb{Z}$ is the set of integers, $w(n)$ is a window of length n , and $X_n(e^{jw})$ is a two-dimensional time-frequency function of n and w .

The implementation process of the algorithm is divided into the following steps:

(1) Sound signal framing and fundamental frequency estimation. In-vehicle acceleration sound samples as time-varying non-stationary signals. The overall noise is mainly composed of each order of noise; the main order component of the four-cylinder engine is the 2nd order and the energy of each other order gradually increases as the speed rises. At the time of frame splitting, set the original signal as $x_m(n) = x(n)w_m(t_m - n)$, $w(n)$ is the window function, and $x_m(n)$ is the m th short time signal after framing. Then, the signal of segment m after adding the window $x_m(n)$ can be expressed as (11):

$$x_m(n) = x(n)w_m(t_m - n) \quad (11)$$

In Equation (11), t_m is the center of the window function and consistent with the estimated marker position of the fundamental frequency.

Then, the frequency of the main order of the sound signal needs to be analyzed; sound clip signals can be considered smooth in short periods of time. Therefore, the sample segments are drawn at a certain frequency in the time domain. It is calculated as (12).

$$f(i) = f_{\min} + i \frac{f_{\max} - f_{\min}}{M - 1} \quad (12)$$

In Equation (12), M is the total number of samples extracted, $i = 0, 1, \dots, M - 1$, and $f_{\min}$ and $f_{\max}$ are the base frequencies of the lowest and highest speed, respectively.

(2) Pitch synchronization mark. Since the main order has quasi-periodic properties, its period can be determined by the position of the zero crossing. The crankshaft rotates for one week and the main order is marked with M zero points. Therefore, the data is marked in $2M$ zero-point intervals for base tone synchronization during a complete engine cycle. This ensures that each sound signal has the same initial phase. The frequency of each marker point corresponds to the predicted instantaneous fundamental frequency and extracts the sound segments corresponding to each fundamental frequency marker point. These segments are labelled in sequence and stored as a set of sound source sample segments [46].

(3) Pitch superposition synthesis. The length of the synthesized sound can be changed by modifying the number of base tones. Modifying the interval between the fundamental markers can change the pitch of the synthesized sound. Decreasing the interval of the fundamental mark makes the pitch higher. Increasing the fundamental interval can lower the pitch of the sound. Finally, the voice segments are overlapped and added together to synthesize the target voice.

Referring to the algorithm idea, when the motion sense sound simulation system is designed, the target sound samples are first processed and edited and then stored in segments. When the sound simulation system intervenes, the corresponding waveform segments are selected according to the vehicle driving state for splicing and synthesizing the acceleration sound.

3. Design of Motion-Sensitive Sound Samples

When the engine is running, the crankshaft rotation will produce vibration and noise response. This noise response is the engine order noise. The order can be expressed as a multiplicative relationship between the rotational speed and the rotational frequency, described as the number of events per rotation week of the rotating structure. The engine noise has typical order characteristics. Order noise is the main component of engine noise; it shows the correlation between engine speed and noise frequency and it is a visual representation of the sound pressure level distribution at different frequencies. Differences in engine sound order components will bring different auditory sensations to the driver. The sound quality and auditory perception of the fuel car interior is closely related to the engine sound; by changing the composition of the engine order sound, it is possible to design acceleration sounds with different feelings [47,48].

This section explores the relationship between sound signals of different order combinations and the perception of auditory features of the sense of motion. Figure 3 shows a sketch of the overall process of characterizing the sense of motion of the engine sound.

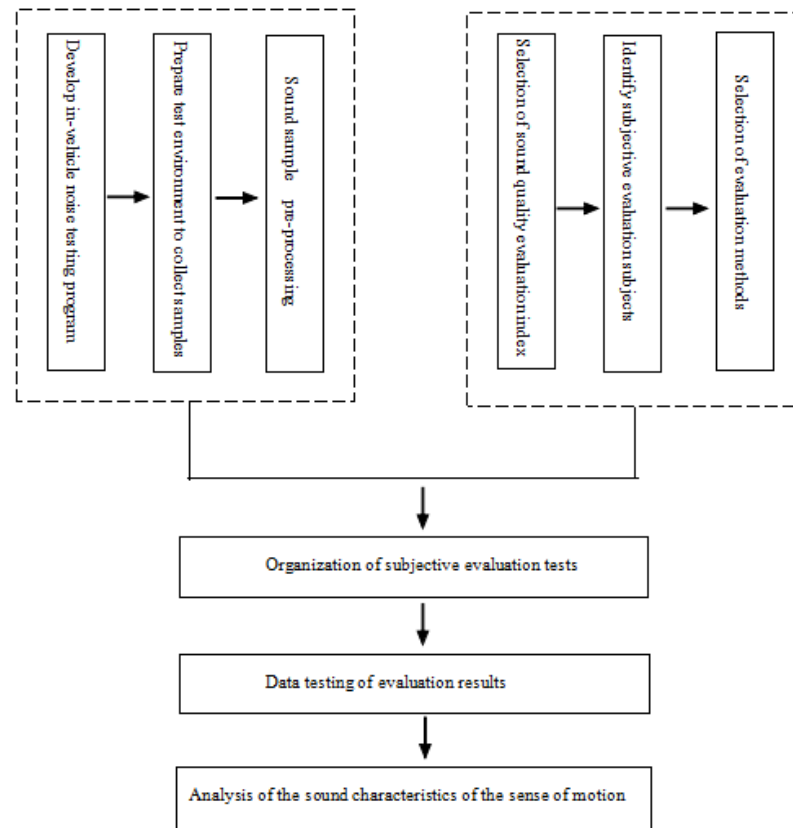


Figure 3. Flowchart of engine sound motion sense analysis.

3.1. In-Vehicle Acceleration Sound Sample Collection

Sound sample acquisition is the basis for research on the characteristics of accelerated sound motion, and the quality of the sound source acquisition is related to the quality of the final simulated sound of the sound simulation system. When collecting acceleration sound samples, vehicle model, collection equipment, test environment, and acceleration range need to be considered to ensure that good acceleration sound samples are obtained.

During vehicle acceleration, the in-vehicle noise is a time-varying non-stationary signal. In order to minimize the impact of tire noise, wind noise, and other disturbing noise on the vehicle acceleration noise collection test, the acceleration sound signal was collected on the NVH drum test bench in the semi-anechoic chamber of the vehicle, where the background noise was below 10 dBA and the windows, entertainment system, and air conditioning were closed during the collection process to avoid interference from other system noise. Referring to “GB1495-2002 Vehicle acceleration outside noise limits and measurement methods” and the driver’s driving habits when accelerating, determine the in-vehicle noise signal acquisition during full-throttle acceleration in 3rd gear of the test vehicle [49]. To ensure that the collected in-vehicle acceleration noise is as realistic as possible, the test uses LMS multi-channel vibration and noise data acquisition equipment and professional GRAS sensors for sound acquisition and recording. Select the corresponding acquisition channel for the sound pressure sensor in the test software, perform sensitivity calibration, and then set the relevant sampling parameters. Since the upper limit of the hearing frequency range of the human ear is about 20 kHz and the highest frequency of twice the hearing is 40 kHz according to Nyquist’s sampling theorem, the sampling frequency is set to 51.2 kHz during acquisition to ensure the true recording of the sound. A vehicle with an inline four-

cylinder engine was selected as the test vehicle, and the specific location of the sensor was installed with reference to “GB/T18697-2002 Acoustics Vehicle Interior Noise Measurement Method” [50]. The in-vehicle noise collection test environment is shown in Figure 4.



Figure 4. In-vehicle noise collection test environment.

During the test, the transmission gear was set to 3rd gear, the sound acquisition equipment was turned on, the acceleration pedal was slowly depressed for a duration greater than 20 s, and the acceleration sound of the engine slowly rising from 1000 r/min to 3500 r/min was recorded in real time. Figure 5 shows the engine speed change curve during the in-vehicle noise collection.

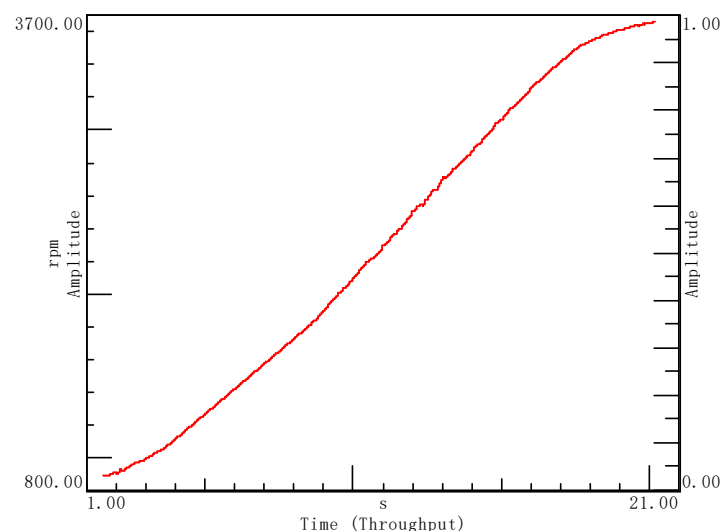


Figure 5. Engine speed variation curve during in-vehicle noise collection.

In order to obtain reliable in-vehicle noise samples and reduce the interference brought by hardware equipment and human operation, two groups of overall tests were conducted during the test. Each group collected the in-vehicle noise signal three times under three acceleration conditions to obtain six sets of initial in-vehicle acceleration noise samples.

3.2. Sound Sample Order Analysis

The collected sound was initially screened, and the sound signal playback function in LMS Test. Lab was used to initially eliminate the disturbed and unstable sound samples in the collection process, and a more ideal group of samples was selected for spectral analysis, as shown in Figure 6 for the sound time domain signal of the intercepted section of acceleration noise in the car under the third gear acceleration condition.

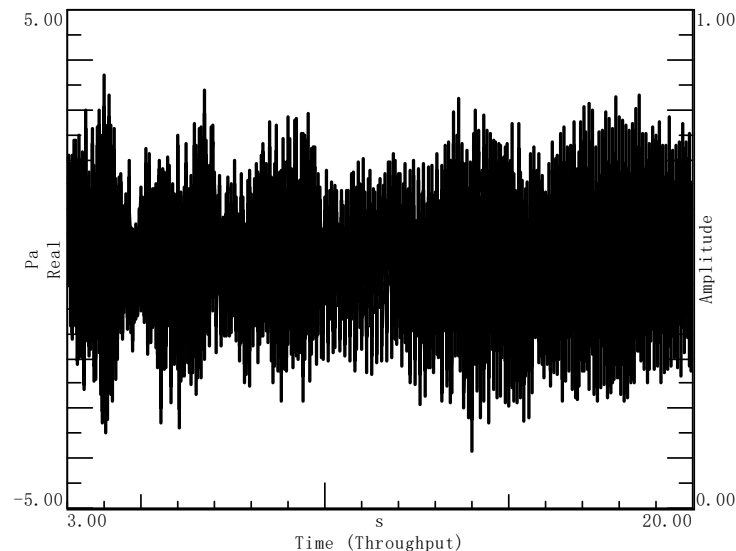


Figure 6. In-vehicle sound signal for acceleration conditions.

The selected acceleration engine sound in third gear can well-reflect the process of acceleration sound change of the vehicle, and the analysis process of other gears is the same. Here, the acceleration sound analysis in third gear is taken as an example. Spectrum analysis and order tracking extraction were performed on the selected sound segments to observe the energy distribution of each order. Figure 7 shows the noise spectrum in the car under the acceleration conditions.

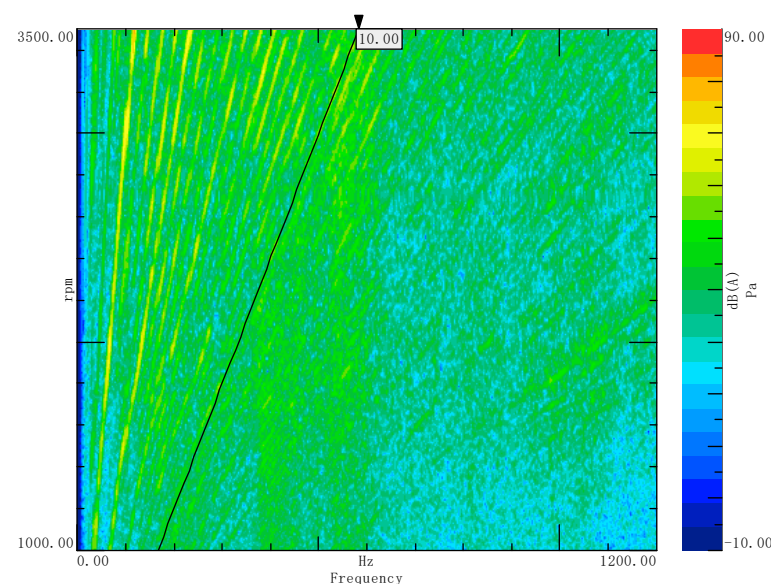


Figure 7. Acceleration noise spectrum in the vehicle under acceleration conditions.

It can be observed that in Figure 7, the noise energy in the car is mainly distributed in the low frequency range of 0–800 Hz, showing an energy distribution dominated by even

and odd orders and supplemented by half-order noise, in which the energy of orders greater than or equal to 10 is very weak, so only the order composition and energy distribution of the first 8 orders are considered in the analysis. The 1st and 2nd order noise order harmonic slices are shown in Figure 8. These two order lines are the two orders with the weakest and strongest spectral energy in the section of noise, respectively, and the other order curves lie roughly within the interval of these two orders.

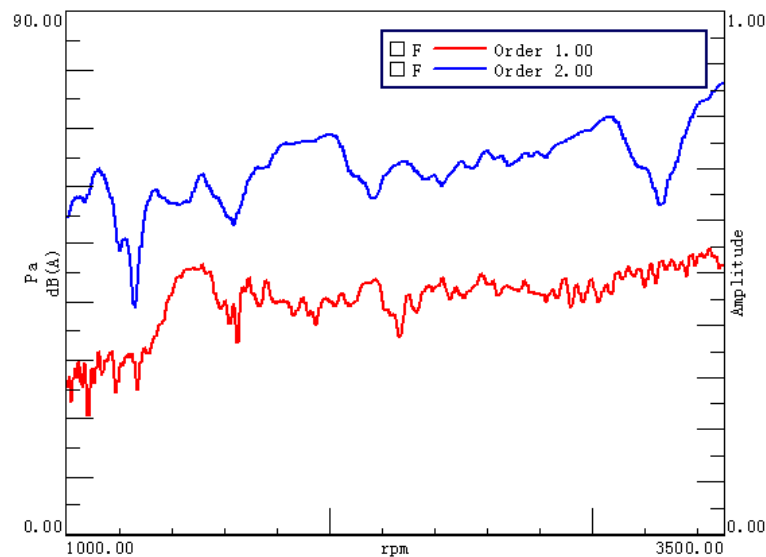


Figure 8. Order harmonic slicing curve.

The even-order noise of a four-stroke engine has a certain impact on the sense of acceleration power, and the odd-order or half-order energy will increase the sound roughness, which has a certain correlation with the subjective feeling of movement [51]. From Figure 7, it can be concluded that the order noise part of the engine sound is mainly composed of odd, even, and half-order noise, so the influence of the acceleration sound composed of these different order noises on the auditory perception of the sense of motion is mainly studied. Table 2 shows the designed order adjustment scheme with samples 1 to 6, indicating the decay and retention for odd, even, and half orders, respectively.

Table 2. Order regulation scheme.

Sample Number	Order Adjustment
YB 1	$-O_1, -O_3, -O_5, -O_7$
YB 2	$-O_2, -O_4, -O_6, -O_8$
YB 3	O_1, O_3, O_5, O_7
YB 4	O_2, O_4, O_6, O_8
YB 5	$O_{2.5}, O_{3.5}, O_{4.5}, O_{5.5}, O_{6.5}, O_{7.5}$
YB 6	$O_1, O_2, O_3, O_4, O_5, O_6, O_7, O_8$

Six groups of different order compositions are designed to produce the sound, filter out the sound within 1000 Hz by low-pass filter, use the adaptive trap filter to adjust the order composition to achieve the order on the harmonic attenuation, enhancement, and minimize the impact on the adjacent harmonics. The notch filter is defined by its center value, width, and attenuation factor, which are expressed as frequency in the time domain and as order in the frequency domain. After analysis and comparison, the harmonic order that the accelerated sound sample needs to be processed is set with a width of 0.15 and an attenuation factor of 40, which can track the corresponding order harmonic noise well. The notch filter order tracking principle is shown in Figure 9.

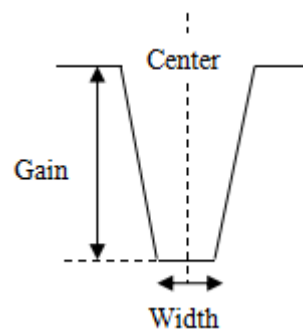


Figure 9. Trap filter order tracking principle.

Six groups of sound samples with different order distributions were obtained. Figure 10 shows the spectrum of the sound samples after order adjustment.

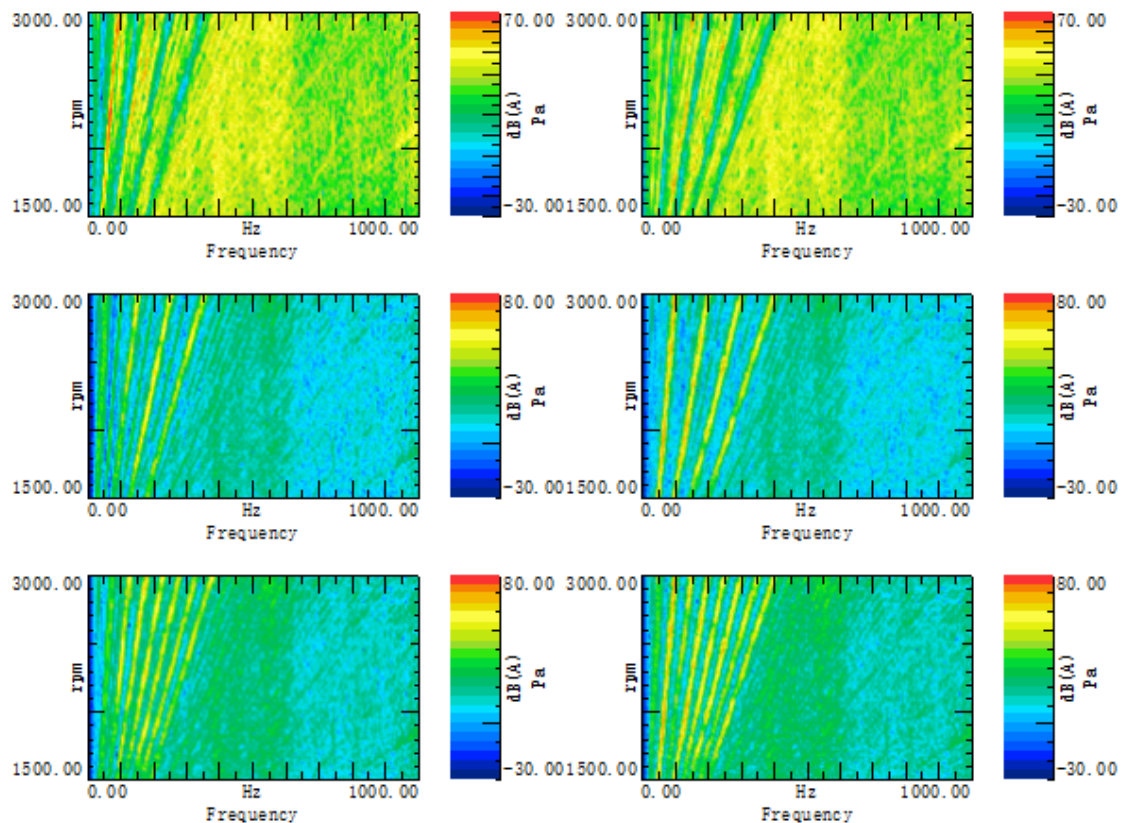


Figure 10. Spectrum of sound samples after order adjustment.

4. Design of Sound Simulation System and Validation of Motion Sensing Target

By building the software and hardware of the sound simulation system, the sound simulation test platform is built. Its role is to verify the function of the simulation system. According to the overall framework of accelerated motion sensing sound simulation system designed in Chapter 2, hardware modules that meet the functional requirements of the system are selected in this chapter. We used LabVIEW program and Keil program to write the system software program. Firstly, the simulation data of the external car driving is sent to the host computer. Then, the characteristics of the synthesized sound and the designed motion sensory sound source are compared and analyzed. Finally, the motion sensory target of sound is verified.

4.1. HAREWARD Scheme of Sound Simulation System

According to the functional requirements of the system design, the MCU Interface Controller & CPU, CAN transceiver, audio storage and speaker, and other main modules are selected. Its purpose is to build the hardware environment of the sound simulation system.

4.1.1. MCU Interface Controller & CPU

MCU is the core component of the whole system. It carries the calculation, judgment, control, and other functions of the system. Additionally, it needs to be selected according to the overall function of the sound simulation system. The MCU chip interacts with external devices through its physical pins. The main external devices include the CAN interface for sending and receiving vehicle message information, the SPI interface for communicating with audio storage module, and the IIS interface for driving audio speaker module. The STM32 series chips launched by ST Microelectronics company have a variety of models and chip resources. It can meet the needs of the sound simulation system. Therefore, STM32F407ZGT6, a mainstream core in the market, is selected as the Interface Controller & CPU. It is an ARM Cortex M3 kernel with a maximum operating frequency up to 168MHz. It is embedded with the CAN controller and DMA controller, has two channels of CAN and sixteen channels of DMA, and three channels of 12-bit ADC and two channels of 12-bit DAC. The chip of this model not only has powerful configuration and rich software resources, but can also meet the functional requirements of the system.

It is worth noting that the CAN controller is embedded in the ARM Cortex M3 kernel microcontroller, which is the basic extension of CAN. It receives commands from the host controller and converts serial bitstream codes into parallel data according to CAN protocol specifications. Furthermore, CAN has a sending buffer to datagram packets and a filter to receive datagram. CAN supports standard frame protocol and extended frame protocol with a baud rate of up to 1 Mbps. There are three operating modes of the CAN controller, namely the working mode, test mode, and debugging mode, among which the working mode and test mode are the most commonly used ones. Figure 11 shows the internal structure of the CAN controller.

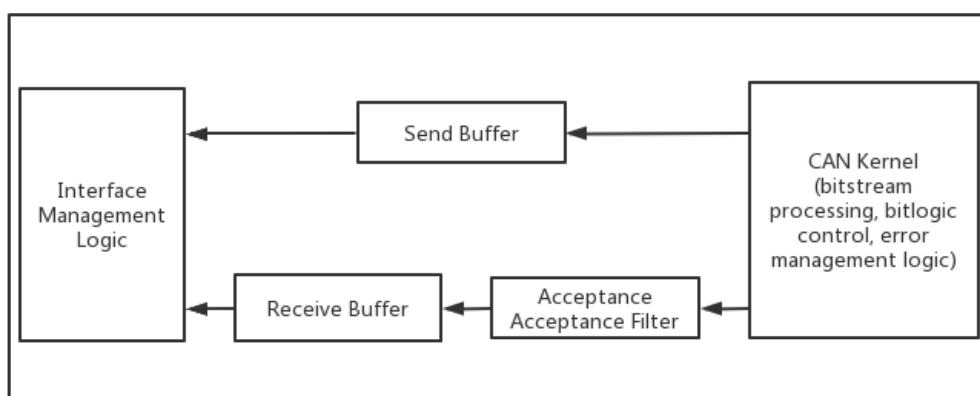


Figure 11. Internal structure of CAN controller.

4.1.2. CAN Transceiver

CAN transceiver is the interface between the CAN controller and vehicle physical bus. The function of CAN transceiver is to convert the binary code flow transmitted by the CAN controller into 1.5 V–3.5 V differential signal and transmit it to the bus during data communication. TJA1050 with good performance is chosen as the transceiver in this paper. This is because its passive state is equivalent to the state off the bus. Additionally, it has low power consumption and strong anti-electromagnetic interference ability. Figure 12 shows the schematic diagram of the CAN bus transceiver circuit.

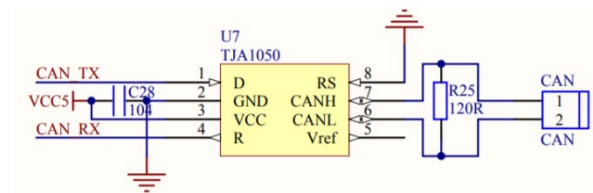


Figure 12. Schematic diagram of CAN bus transceiver circuit.

4.1.3. Audio Storage Module

For audio storage, we selected a SD card because its storage capacity is relatively large compared with flash memory. Its volume compared with a U disk not only has unique advantages, but also supports SPI/SDIO drive. Therefore, the standard SD card is selected as the storage device of the sound source fragment of motion sensing characteristics. Using the SDIO driver of the main control chip, the communication rate can reach 24 MHz, and the data transmission rate can be up to 12 M bytes, meeting the audio reading requirements. Figure 13 shows the circuit schematic diagram of the selected audio storage module.

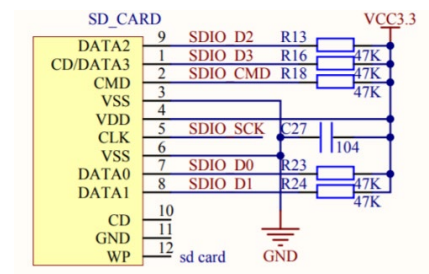


Figure 13. Schematic diagram of audio storage module circuit.

4.1.4. Audio Decoding and Speaker Module

The audio format decoding module chooses VS1053 as the chip. It is connected with the single chip microcomputer interface through 9 pins, with a 3.3-V power supply, SPI communication, compact size, and simple programming characteristics. Figure 14 shows the pin interface of the audio decoding module chip. The audio power amplifier module selects the TPA3116D2 chip. The working voltage of the module is 4.5~27 V; it has two 50 W stereo dual channel, SNR up to 102 dB, an on-board volume adjusting knob, an audio input interface, and a horn terminal.

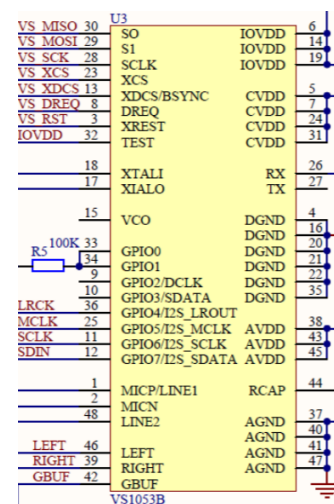


Figure 14. Audio decoding module chip pin interface.

4.2. Programming of Sound Simulation System Software

The software program, written using NI company, has powerful functions in the embedded domain. It has a LabVIEW-embedded development module for the ARM microcontroller; using LabVIEW, call Keil uVision software to write the program code. LabVIEW has very powerful functions in the embedded field and supports a variety of embedded hardware development. Table 3 shows common embedded hardware supported by LabVIEW.

Table 3. Common embedded hardware supported by LabVIEW.

Hardware Types	Advantages	Disadvantages
MCU(8051)	Easy to program; Small volume; The cost is low	It cannot be used in high-performance applications
CPU(ARM7)	Performance is good; Efficient application; Programming easier	Power consumption is higher
DSP	Dedicated to handling floating point numbers	The processing mechanism is a sequential structure
FPGA	Reprogrammable circuit; High hardware flexibility	The high cost; Power consumption of the big

Program development using the ARM firmware package of LabVIEW Embedded modules covers most of the embedded general-purpose chips and continues to be updated. It supports the direct development of ARM Cortex-M3, ARM7, ARM9, and other embedded processors, and its generated EXE program files can also be directly run in Keil company's RTX real-time operating system, Lineo company's Uclinux real-time operating system, and other embedded operating systems. In program development, using structure and control functions in the LabVIEW environment can save a lot of effort. Programmers can focus on program functionality and execution order. Furthermore, programmers can achieve on-line real-time debugging through the input and display control of the front panel. Download and install the LabVIEW embedded module toolkit for ARM microcontrollers. The Keil uVision integrated development environment for embedded systems is designed and developed jointly with Keil Company in Germany. These can call the Real View compiler for real-time embedded programming, simulation debugging, communication drivers, and control of various I/O drivers and a series of functions. The program structure design, data array operation, and file input and output functions are realized in LabVIEW. These functions can be automatically created by LabVIEW's C code generation technology, and write program functions corresponding to embedded applications. Figure 15 shows the software architecture of ARM programming with LabVIEW.

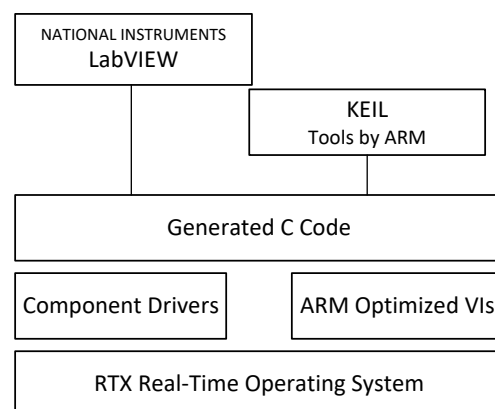


Figure 15. Software architecture of ARM programming by LabVIEW.

When programming the program, firstly, LabVIEW is used to build graphical control parts to realize the programming of each part of the program. Then, C code generation technology is used to convert the written VI program into C code for Keil to call. Next, through the firmware driver and hardware driver of the ARM chip, the program is combined with the underlying hardware. Finally, through RTX real-time operating system, a number of threads are created with different functions to achieve parallel running. Figure 16 shows the development process of RAM using LabVIEW.

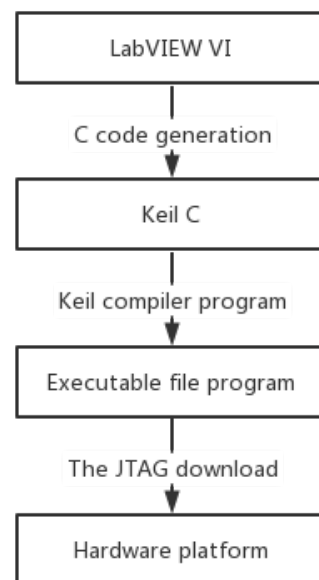


Figure 16. Development process of RAM by LabVIEW.

This embedded module can quickly design program functions by using graphical controls, and the operation of registers in hardware can be directly encapsulated into graphical function calls, which is convenient to realize corresponding functions. The program mainly includes related peripheral chip, GPIO port initialization, CAN interface, CAN shield register, audio storage, audio reading, and decoding module configuration. When configuring a CAN interface, you need to set the baud rate. The baud rate and the CAN bit time are reciprocal to each other. In STM32, a normal bit time is divided into three segments: synchronization segment, time segment 1, and time segment 2. For the purpose of setting the baud rate, the sum of the corresponding values of the three segments is then taken as the reciprocal. Here, the sampling point is the point at which the bus level is read and taken as the bit value. Figure 17 shows the normal bit time of CAN.

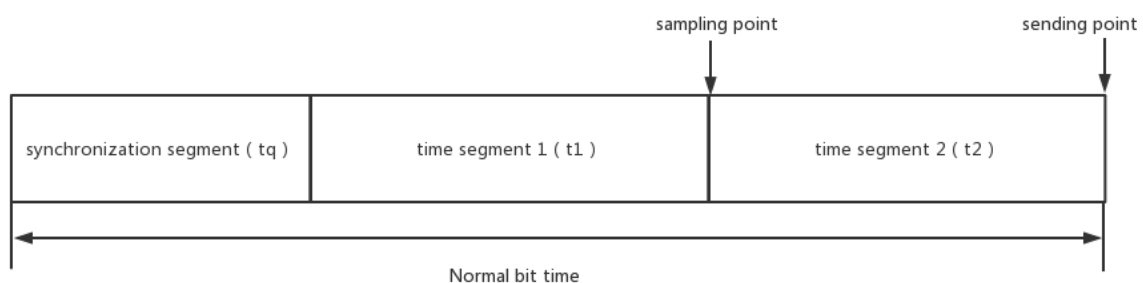


Figure 17. CAN normal bit time.

In the program design, one first needs to create a new ARM project in LabVIEW. Then, call peripheral drivers such as CAN, SPI, and DAC corresponding functions. The program uses the modular programming idea and designs the program running frame and the sequence. According to the configuration of function interface parameters, the underlying

hardware interface is associated with the development hardware platform. Figure 18 shows the software execution flow of the sound simulation system.

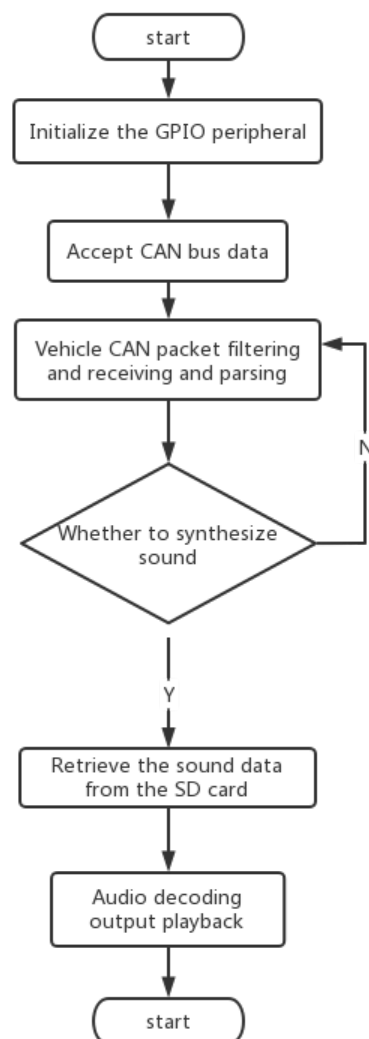


Figure 18. Sound simulation system software execution flow.

The main programming process of the software is as follows:

Initialize peripherals and GPIO: Call corresponding functions for used peripherals such as CAN controller and SD card to initialize and configure the interface of the function. For example, the CAN communication initialization function is called to configure the GPIO interface of CAN sending and receiving. Additionally, the baud rate and working mode of communication are also set.

Configure the CAN interface: Use the CAN send function to configure the specific parameters of the CAN interface. The value includes the identifier of the sent packet, packet type, data carried by the packet, and the total length of the packet.

Configure CAN filters and parse packets: The configuration of the CAN filter function determines the identifier and frame type of the received packet. Determine whether you care about a specific packet or a group of packets when setting the mask. Through CAN packets, the read function receives the number of packets in the read and fetch buffer and obtains the specific packet data of each frame. Combined with the definition of CAN message format, the actual physical value of vehicle running state is calculated.

Sound synthesis condition judgment: Information such as accelerator pedal opening value and speed is obtained by index analysis. The values of the two are determined. If the

conditions are not met, the next pedal opening value will be read and the difference value will be taken with the last value. If the conditions are met, the value will be output.

Sound file retrieval and playback: The corresponding sound segments are indexed in real time according to the acceleration pedal opening value, and the synthesized sound is output for playback. If the brake pedal value is detected to be not zero, stop the sound playback.

4.3. Construction of Test Platform for Accelerated Motion SenseSound Simulation System

4.3.1. CAN Signal Acquisition and Simulation of Real Vehicle

For the acquisition of CAN data of real vehicles, it is necessary to carry a whole set of equipment to the vehicle for acquisition, which consumes a lot of time in the system debugging stage. Therefore, it is suggested to use a simple portable device to simulate the real vehicle driving status message. Due to the differences of different auto manufacturers and suppliers, the definitions of CAN packets for vehicle state parameters of different models are different. According to the principle of obtaining CAN message through the OBD interface of automobiles, select the CAN controller and transceiver identified in the previous section. Form vehicle CAN signal acquisition device. In addition, the real vehicle message of a pure electric vehicle is collected, and the data on the CAN bus is monitored and recorded. Figure 19 shows the collection and recording of bus data of a pure electric vehicle.

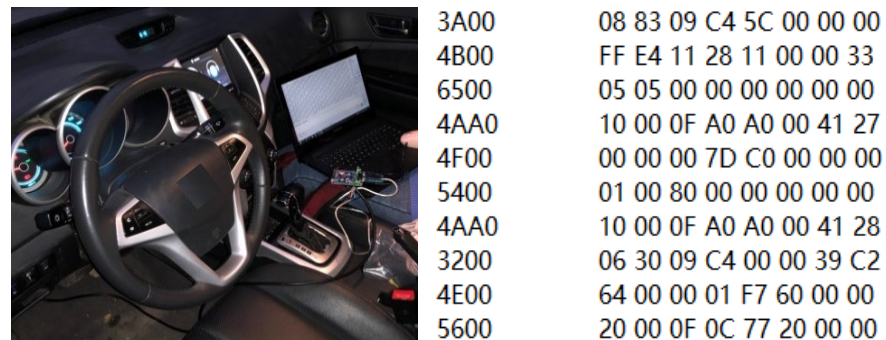


Figure 19. Collection and recording of bus data of a pure electric vehicle.

Consider the debugging efficiency and difficulty of the sound simulation system combined with the situation of the real car to obtain the message. Taking the CAN communication matrix defined by this pure electric vehicle as an example, the data area is carried with the speed. The CAN message identifier of accelerator pedal opening information is set as 0×255 . The identifier of CAN message carrying brake pedal information in the data area is simulated as 0×153 . All are standard data frames. Then, the receiving ids of the mask of the CAN filter are set to $0 \times 4AA0$ and $0 \times 2A60$, respectively, and the two groups of filters are enabled to receive CAN packets carrying the information of vehicle speed, accelerator pedal, and brake pedal. The CAN analyzer is used as the data simulation transmission device and a certain USBCAN-II device is selected, whose data transmission capacity is 4000 frames/s and baud rate range is 5K~1M. It also supports CAN2.0A and CAN2.0B protocols, and has a built-in 120 Ω matching resistance, which CAN meet the requirements of CAN data receiving and receiving simulation. The upper computer that CAN send the simulated real car CAN signal developed secondary in Section 4.2 is used. Figure 20 shows the CAN data sending process of the upper computer. After the format of CAN message is set, the speedometer and accelerator pedal are operated to realize the simulation of vehicle CAN signal in acceleration state.

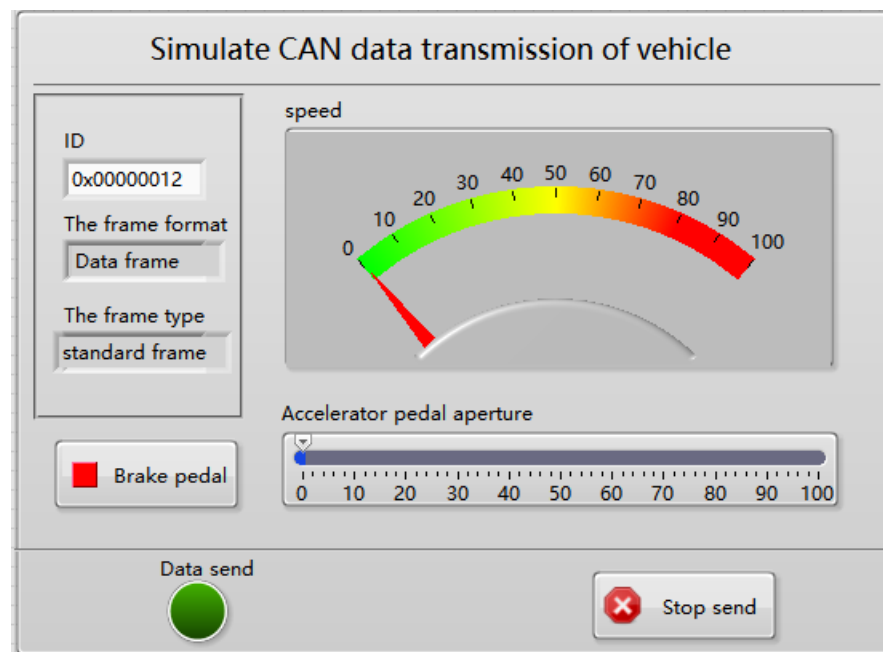


Figure 20. CAN data sending process of the upper computer.

4.3.2. Connecting Hardware Modules

Considering the difficulty and cost of implementation and the selection of main hardware modules, the STM32F407 single-chip development platform with the main control chip and basic peripherals meeting the system design requirements is selected. Firstly, connect one end of the USBCAN-II device to the upper computer. Then, the terminal is connected to the CAN transceiver interface of the main control chip. Finally, the module is connected with the development platform, and the on-board 5 V power supply of the STM32 microcontroller is used to power the VS1053 audio decoding module. The corresponding pins of the main control chip are externally connected to the VS1053 audio decoding module, and the corresponding seven pins are data chip selection pin XD_CS, SPI clock bus pin SCK, SPI bus data input and output pins MOSI and MISO, chip selection input pin XCS, reset pin RST, and data request pin DREQ. The DREQ pin will be pulled up to receive the transmitted audio data block. After receiving, the pin will be pulled down and the next time it needs to be received, the pin will be raised, so that the reception and decoding output of the audio data stream will be repeated. Figure 21 shows the physical connection between the audio decoding module and the pin of the main control chip.

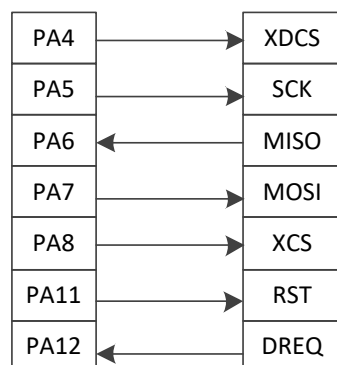


Figure 21. Connection relationship between audio decoding module and main control chip pin.

The VS1053 audio decoding module has an audio output interface, which can be directly connected to the audio input interface on the audio power amplifier module. The

sound amplitude can be changed by adjusting the knob on the power amplifier module. The loudspeaker is connected to the terminal of the power amplifier module. Figure 22 shows the connection relation of the test platform of a sound simulation system.

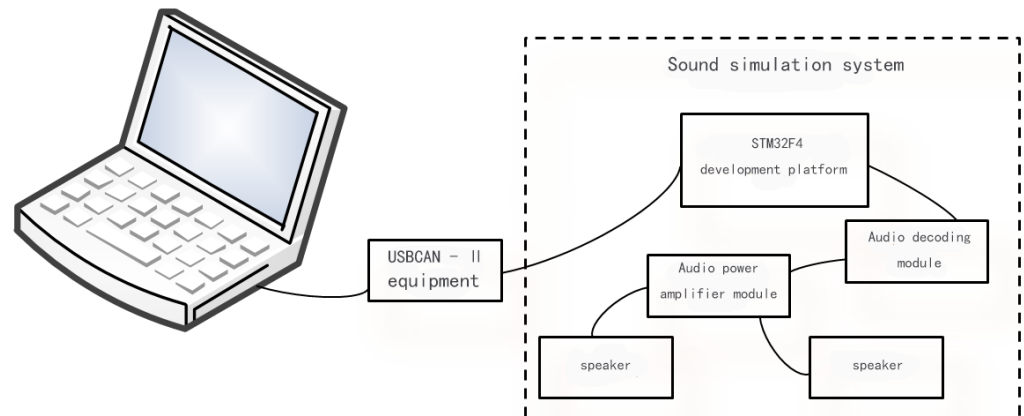


Figure 22. Connection relationship of the test platform of a sound simulation system.

4.4. Validation of Motion Sensing Sound Targets

The function of the sound simulation system is to simulate the engine sound with motion sense auditory feeling when the pure electric vehicle is accelerating. It is a simulation of sound dynamics to achieve driver interaction with vehicle acceleration behavior.

According to the hardware selection and the connection relationship of each module, the hardware system of sound simulation is constructed. Firstly, the written software generates C code in LabVIEW, and then calls Keil uVision to jointly compile it into an executable file, and finally downloads it to the main control chip of the hardware through the JTAG simulator.

First, the USBCAN-II device, vehicle loudspeaker, computer, and other hardware are connected to the sound simulation system, and then CAN is used to send the host computer to send vehicle driving data packets to the sound simulation system. Finally, the accelerated sound is actively simulated by the loudspeaker after the main control chip is calculated. Call the computer sound card correlation function using LabVIEW. The simulated accelerated sound acquisition is recorded and saved in the form of wav file and compared with the input sound source of motion sense characteristics designed to determine the function realization of debugging sound simulation system design. Figure 23 shows the test platform of accelerated motion sense sound simulation system.

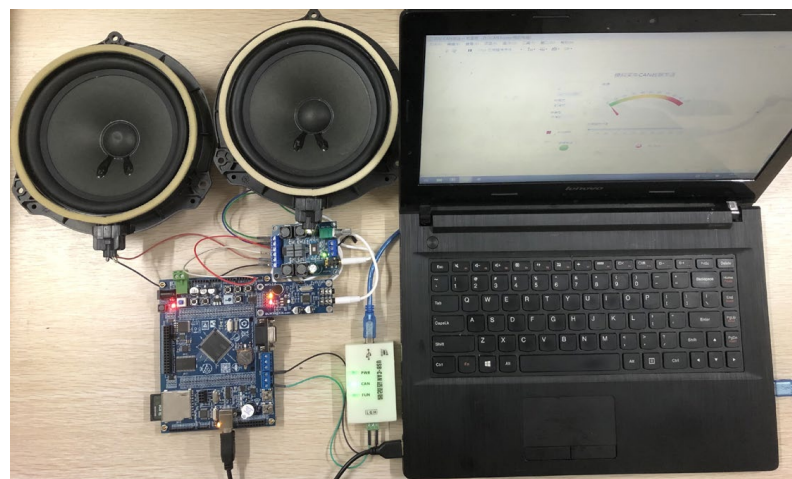


Figure 23. Test platform of accelerated motion sensing sound simulation system.

The sound synthesis of the accelerator pedal is simulated in the three intervals of 0~30%, 30~60%, and 60~90%. The sound pressure level in the car can be adjusted by the gain of the power amplifier during acceleration. Figure 24 shows the pedal opening signal changes under different acceleration conditions.

The collected wav files were imported into LMS Test Lab for time-frequency analysis. Figure 25 shows the time domain diagram of synthesized sound signals under the change of pedal aperture of 0~30%, 30~60%, and 60~90%, respectively.

As can be seen from Figures 25 and 26, when the sound simulation system is working, the synthesized sound under different pedal aperture can dynamically adapt to the change of vehicle state. With the increase of accelerator pedal aperture, the amplitude of synthesized sound gradually increases, and the frequency distribution of sound energy gradually increases, and the order harmonic distribution is basically consistent with the characteristics of the designed motion sensing sound source. With pure odd order harmonics as the main sound components, the motion sense order characteristics of the simulated synthesized sound are verified. The synthetic sounds above add to the driving experience.

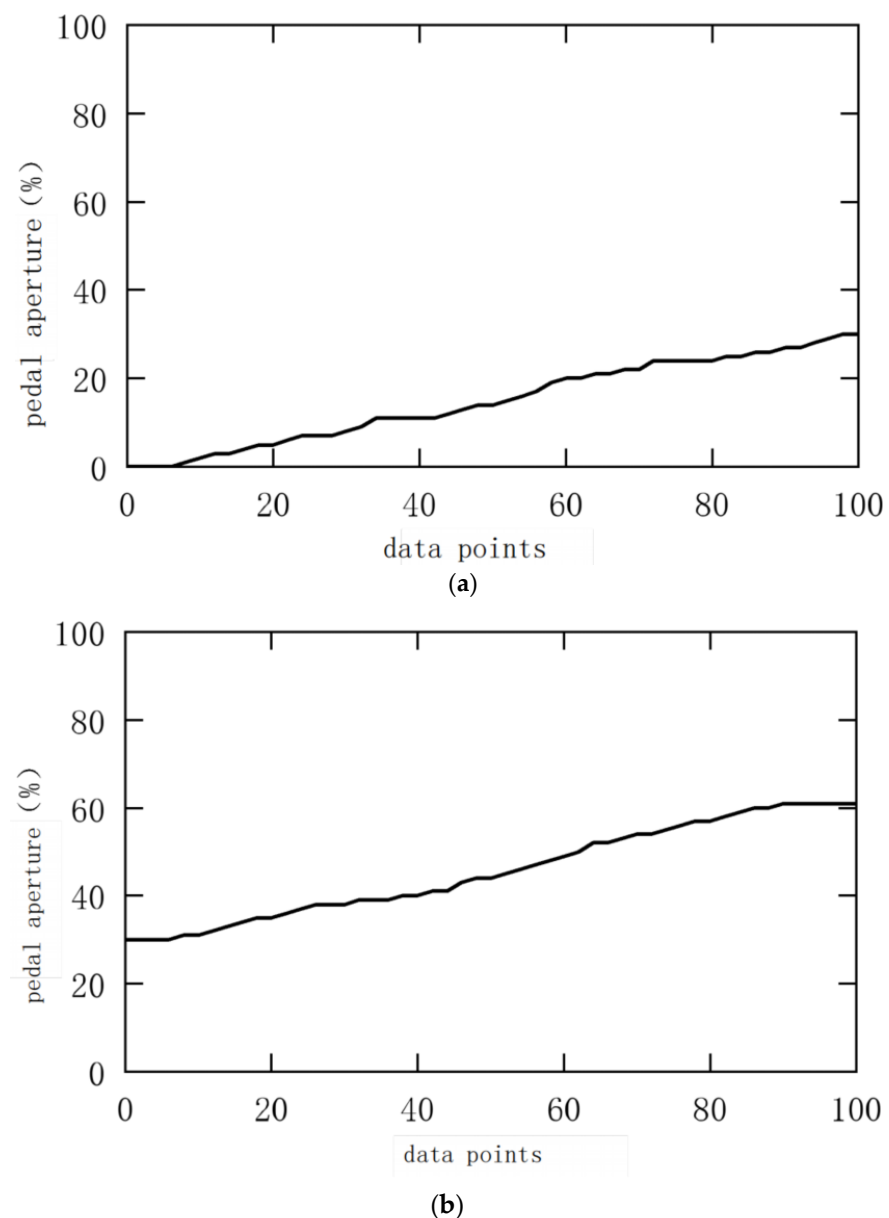


Figure 24. Cont.

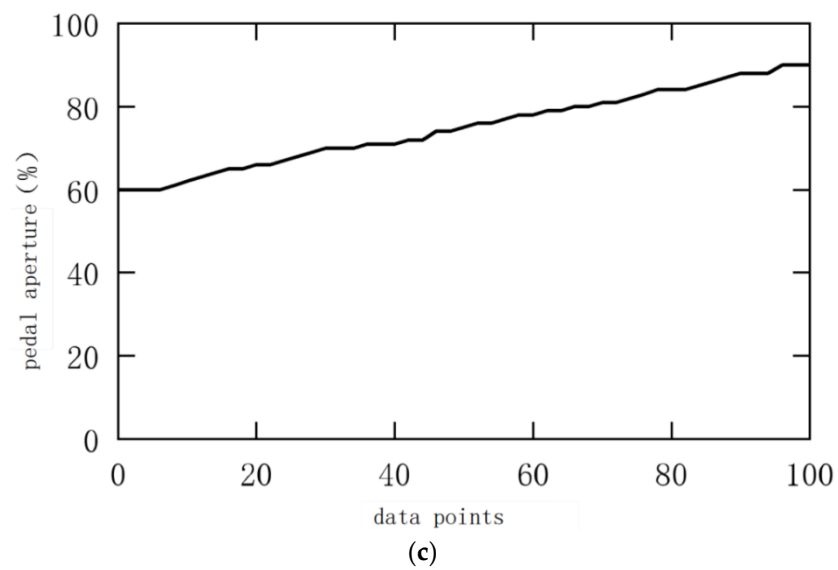


Figure 24. Pedal aperture signal changes under different acceleration conditions. (a) Accelerator pedal aperture 0–30%. (b) Accelerator pedal aperture 30–60%. (c) Accelerator pedal aperture 60–90%.

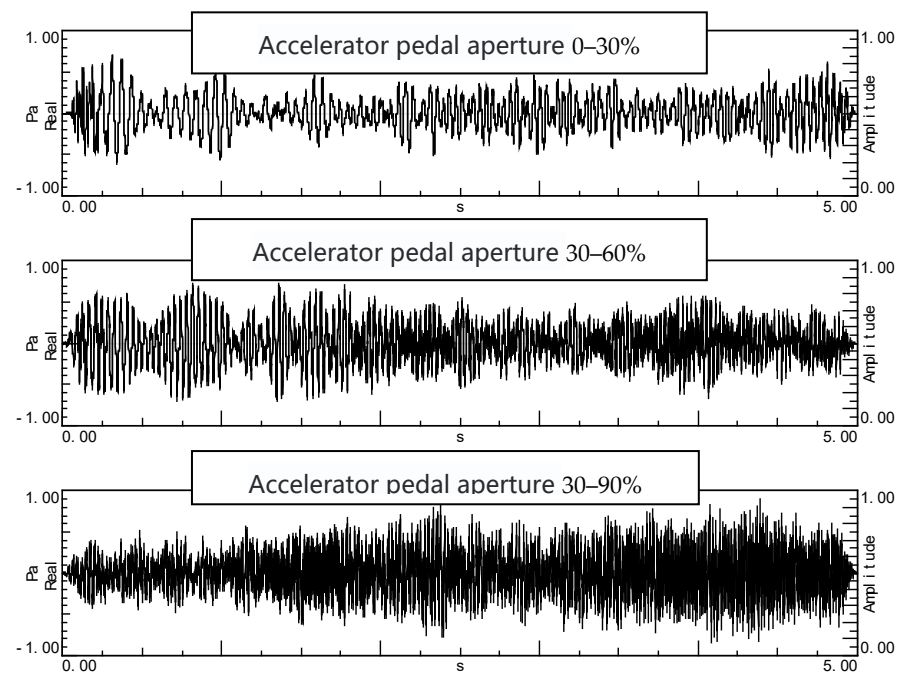


Figure 25. Synthesized sound signals under different accelerator pedal aperture changes.

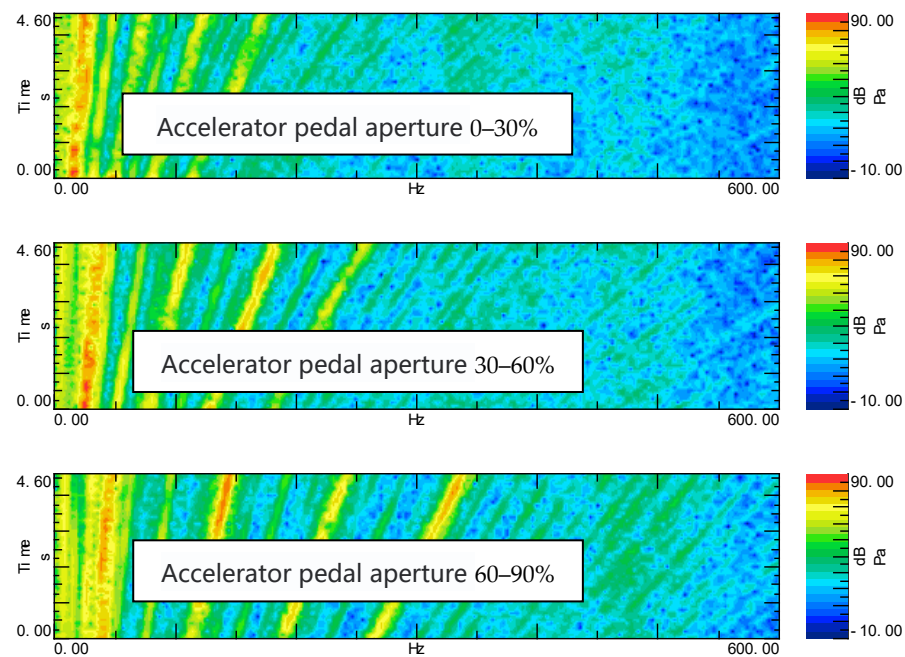


Figure 26. Synthesized sound spectrum under different pedal aperture.

5. Conclusions

In this paper, the acceleration sound simulation system of an electric vehicle is studied. By reading the driving state data on the CAN bus of an electric vehicle, the goal of engine motion sensation sound simulation in the process of acceleration is realized, thus enhancing driving feedback and improving user driving experience.

This paper studies the design method of engine acceleration motion sensory sound simulation systems. Centering on sound design and sound simulation, the target feature sound source is designed using signal processing technology. By reading the vehicle CAN signal to identify vehicle working condition, dynamic sound simulation is carried out. A sound synthesis strategy was developed.

In this paper, latest platform of acceleration motion sound simulation system is built, and the sensory target of acceleration motion is verified. Through the hardware chip and function module of the sound simulation system, the joint debugging of hardware and software is realized. The test platform of sound simulation system is built by combining the CAN adapter with system hardware and software. The synthetic sound is collected in the three ranges of 0–30%, 30–60%, and 60–90% of the accelerator pedal to realize the sound simulation of electric vehicle acceleration.

Author Contributions: J.F. is responsible for the technical route of the full text. C.Z. is responsible for the full text program writing. J.S. was responsible for the full text writing and overall planning. All authors have read and agreed to the published version of the manuscript.

Funding: Supported by Chongqing Natural Science Foundation of China (cstc2020jcyj-msxmX0226).

Institutional Review Board Statement: All agencies are correctly signed.

Informed Consent Statement: All contributors agree to publish by byline.

Data Availability Statement: All data are true and valid.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Abbreviations	Detailed
CAN	Controller Area Network
OBD	On-Board Diagnostic
GPIO	General-Purpose Input/Output Ports
SPI	Serial Peripheral Interface
DAC	Digital to analog converter
SD	Secure Digital Memory Card
SDIO	Secure Digital Input and Output
SPI/SDIO	Serial Peripheral Interface/Secure Digital Input and Output
MCU	Microcontroller Unit
CPU	Central Processing Unit/Processor
DMA	Direct Memory Access

References

1. Ou, L.Q. Research on the transformation and development of Chinese automobile industry from the perspective of low carbon economy. *Strait Sci.* **2010**, *11*, 44–60.
2. Editorial Department of ‘China Journal of Highway’. Academic research review of china automotive engineering. *China J. Highw.* **2017**, *30*, 1–5.
3. Amman, S.A.; Das, M. An efficient technique for modeling and synthesis of automotive engine sounds. *IEEE Trans. Ind. Electron.* **2002**, *48*, 225–234. [\[CrossRef\]](#)
4. Genuit, K.; Bray, W.R. Prediction of sound and vibration in a virtual automobile. *Sound Vib.* **2002**, *36*, 12–19.
5. Rensburg, T.V.; Wyk, M.V.; Potgieter, A.T.; Steeb, W.-H. Phase vocoder technology for the simulation of engine sound. *Int. J. Mod. Phys. C* **2006**, *17*, 721–731. [\[CrossRef\]](#)
6. Heitbrink, D.A.; Cable, S. Design of a driving simulation sound engine. In Proceedings of the Driving Simulation Conference, North America 2007 (DSC-NA 2007), Iowa City, IA, USA, 12–14 September 2007.
7. Kubo, N. Signal processing in sound designing of additive engine sound for electric vehicle and hybrid vehicle. In Proceedings of the INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Osaka, Japan, 4–7 September 2011.
8. Zhekova, I. *Time-Frequency Analysis and Granular Synthesis of Diesel Engine Noise at Idle: Application for a Perceptive Study in the Context of the Auditory Scene Analysis*; HAL CCSD: Lyon, France, 2007.
9. Boussard, P.; Molla, S.; Orange, F. Comprehensive process for car engine sound design: From signal processing to an audio system integrated in the vehicle. In Proceedings of the INTER-NOISE and NOISE-CON Congress and Conference Proceedings, New York, NY, USA, 19–22 August 2012.
10. Jagla, J.; Maillard, J.; Martin, N. Sample-based engine noise synthesis using an enhanced pitch-synchronous overlap-and-add method. *J. Acoust. Soc. Am.* **2012**, *132*, 3098–3108. [\[CrossRef\]](#)
11. Gwak, D.Y.; Yoon, K.; Seong, Y. Application of subharmonics for active sound design of electric vehicles. *J. Acoust. Soc. Am.* **2014**, *136*, EL391–EL397. [\[CrossRef\]](#)
12. Matthias, F.; Franz, Z.; Alois, S.; Stephan, B.; Christian, K. Comprehensive array measurements of in-car sound field in magnitude and phase for active sound generation and noise control. *SAE Int. J. Passeng. Cars-Electron. Electr. Syst.* **2014**, *7*, 596–602.
13. Ahrens, D.; Fox, D.; Feng, D. Active methods for unrestricted sound design. *Auto Tech Rev.* **2014**, *3*, 44–47. [\[CrossRef\]](#)
14. Welsh, D.; Gomez, A.; Pierce, J. Designing an interior and exterior acoustical brand identity for electric vehicles by means of sound synthesis. In Proceedings of the INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Chicago, IL, USA, 26–29 August 2018.
15. Wang, L.X.; He, J.X.; Huang, F.Z. Research and application of speech processing system in electric vehicle sound simulator. *J. Jilin Univ. Archit. Eng.* **2012**, *30*, 57–60.
16. Hu, D.Y. Research on Automotive Active Sound Management System. Master’s Thesis, Jilin University, Changchun, China, 2017.
17. Jia, Y.Q. Automotive Engine Sound Simulation System Design. Master’s Thesis, Suzhou University, Suzhou, China, 2018.
18. Hang, L.Q. Research and Dynamic Realization of Vehicle Driving Simulation System. Master’s Thesis, Southwest Jiaotong University, Chengdu, China, 2018.
19. Cao, Y.T. Research on Design and Evaluation Method of Electric Vehicle Active Vocalization System. Ph.D. Thesis, Jilin University, Changchun, China, 2019.
20. Zhu, B.; Zhang, J. Real-time synthesis of engine sound effects based on continuous speed samples. *Comput. Appl. Res.* **2020**, *S2*, 123–125.
21. Cao, S.M. Research on the Design of Prompt Sound for Low-Speed Driving of Electric Vehicles at Urban Traffic Intersections. Master’s Thesis, South China University of Technology, Guangzhou, China, 2020.
22. Pan, L.; Lin, L.; Gu, Y. Automotive active sound design based on particle algorithm. *Shanghai Automot.* **2019**, *7*, 27–30.
23. Wang, W. Application of voice feature classification in active voice design of new energy vehicles. *Shanghai Automot.* **2020**, *3*, 6–9.

24. Chen, Z.L. Application of motion-sensing exhaust sound synthesis technology in pure electric vehicles. *Automot. Technol.* **2020**, *6*, 13–16.
25. Solomon, L.N. Semantic reactions to systematically varied sounds. *J. Acoust. Soc. Am.* **1959**, *31*, 986–990. [[CrossRef](#)]
26. Sottek, R.; Krebber, W.; Stanley, G. *Tools and Methods for Product Sound Design of Vehicles*; SAE International: Troy, MI, USA, 2005.
27. Lu, M.H.; Jen, M.U. Target setting for enhancing sound quality of a motorcycle by sound synthesis technique. *Noise Control. Eng. J.* **2016**, *64*, 44–55. [[CrossRef](#)]
28. Takao, H.; Hashimoto, T.; Hatano, S. Quantification of subjective unpleasantness using roughness level. In Proceedings of the Noise & Vibration Conference & Exposition, Williamsburg, VA, USA, 2–5 May 1993.
29. Biermayer, W.; Thomann, S.; Brandl, F. A software tool for noise quality and brand sound development. In Proceedings of the SAE Noise & Vibration Conference & Exposition, Traverse City, MI, USA, 30 April–3 May 2001.
30. Ishii, Y.; Iwai, M.; Ito, K.; Yamashita, T. A support system for development of sporty sound and its application. In Proceedings of the SAE 2003 Noise & Vibration Conference and Exhibition, Traverse City, MI, USA, 5–8 May 2003.
31. Noumura, K.; Yoshida, J. Perception modeling and quantification of sound quality in cabin. In Proceedings of the SAE 2003 Noise & Vibration Conference and Exhibition, Traverse City, MI, USA, 5–8 May 2003.
32. Mao, D.X. *Subjective Evaluation and Analysis Method of Car Interior Sound Quality*; Tongji University: Shanghai, China, 2003.
33. Yu, W.Z.; Mao, D.X.; Wang, Z.M.; Hong, Z.H. Subjective evaluation of car interior noise. *Acoust. Technol.* **2002**, *4*, 181–184.
34. Jiao, F.L.; Liu, K. Sound quality research in the field of noise control brief introduction: Subjective evaluation. In Proceedings of the Kunming: National Conference on Environmental Acoustic Electromagnetic Radiation Environment, Kunming, China, 6–10 October 2003; pp. 11–14.
35. Jiao, L.; Liu, K. Subjective evaluation of noise sound quality using multidimensional scaling analysis. *Acoust. Tech.* **2004**, *23*, 95–96.
36. Mao, X.D.; Yu, Z.W.; Wang, M.Z. Data test and criterion for paired subjective evaluation of sound quality. *J. Acoust.* **2005**, *30*, 468–472.
37. Mao, X.D.; Gao, L.Y.; Yu, Z.W.; Wang, M.Z. Comparative study on subjective evaluation of sound quality. *J. Acoust.* **2005**, *30*, 515–520.
38. Jiao, L.F.; Liu, K.; Mao, X.D. New characteristics of data analysis in the subjective evaluation of noise sound quality. *Acoust. Tech.* **2005**, *24*, 107–108.
39. Jiao, L.F. Subjective evaluation of crowd classification and interior noise quality. *Acoust. Tech.* **2006**, *25*, 568–572.
40. Jiao, L.F.; Liu, K.; Mao, X.D. Subjective evaluation of noise sound quality based on non-metric multidimensional scaling analysis. *J. Acoust.* **2005**, *6*, 43–51.
41. Shen, Z.Z.; Song, Y.Y. Analysis of related factors affecting vehicle sound quality audition experiment. *Noise Vib. Control* **2008**, *28*, 97–100.
42. Pang, J.; Chen, G.; He, H. *Automotive Noise and Vibration*; Beijing Institute of Technology Press: Beijing, China, 2006.
43. Chen, Y.Z. Development of Engine Excitation Analysis and Powertrain Torsional Vibration Simulation Software. Master's Thesis, Jilin University, Changchun, China, 2006.
44. Li, Y.; Wei, D.; Wang, Y.L. Emotional speech synthesis based on PSOLA and DCT. *Comput. Eng.* **2017**, *43*, 278–291.
45. Lu, B. Research and Implementation of Embedded Speech Synthesis and Key Algorithms. Master's Thesis, Xidian University, Xi'an, China, 2009.
46. Zhang, X. Research and Implementation of Active Sound Wave System in Electric Vehicle. Master's Thesis, Shijiazhuang Railway University, Shijiazhuang, China, 2021.
47. Ohsasa, Y.; Kadomatsu, K. Sound quality evaluation of exhaust note during acceleration. In Proceedings of the SAE Noise & Vibration Conference and Exhibition, Honolulu, HI, USA, 23–27 July 1995.
48. Norio, K. Sound marketing on engine sound design. In Proceedings of the INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Hamburg, Germany, 21–24 August 2016; Volume 253, pp. 5872–5876.
49. General Administration of Quality Supervision, Inspection and Quarantine. *GB/T 18697-2002 Acoustics: Measurement Methods for Noise in Automobiles*; China Standard Publishing House: Beijing, China, 2002.
50. General Administration of Quality Supervision, Inspection and Quarantine. *GB/T 1495-2002 Limits and Measurement Methods for Exterior Noise of Accelerating Vehicles*; China Standard Publishing House: Beijing, China, 2002.
51. Du, S.Z. *Acoustic Quality Control and Optimization Study of Automotive Engine Intake System*; Wuhan University of Technology: Wuhan, China, 2019; Volume 7.

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