

Active Sound Control Technology for Electrified Vehicles Based on Concept of Shepard Tones

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ABSTRACT

Active Sound Control technology for electrified vehicles was developed in order to realize vehicle interior sound levels matching the seamless acceleration that is characteristic of driving under electric motor power. This technology takes the fundamental approach of generating sound based on the conceptual approach of Shepard tones and synchronizing it with the vehicle velocity. The main tones generated according to the theory of Shepard tones are superimposed with multiple sub-tones at preset frequency ratios. This approach can produce acceleration sounds with further increased freedom. An acceleration sound that differs from engine sound and has sounds matched to the electrified vehicle has been realized by means of this technology.

1. Introduction

Among measures addressing global warming and other such environmental issues is the use of electrified vehicles (x Electrified Vehicle: xEV), which includes hybrid vehicles, fuel cell vehicles, and battery-powered electric vehicles. Advances are being made in the development and popularization of such vehicles. The electrification of power plants, however, has raised new challenges in the design of interior sound for vehicle cabins. When an EV is operating by motor, the absence of sound generated by an internal combustion engine makes the vehicle cabin quiet, but on the other hand, the feeling of acceleration that vehicle occupants gain from sound when the vehicle is accelerating is diminished⁽¹⁾. Furthermore, acceleration sound as one element that forms the identity of the vehicle is also lost.

The cabin interior sound from conventional engines is often sensed as noise. However, the sound functions not only to make vehicle occupants aware of vehicle acceleration and deceleration, but is also an element that can express the individual character of the particular automobile manufacturer. Each manufacturer has, therefore, been creating acceleration sounds to include as part of its own brand identity^{(2),(3)}. The authors have created an Active Sound Control (ASC) technology intended to enhance the acceleration feel of engine-powered vehicles as well as to construct sounds that are in line with the brand identity of

those vehicles, and they have applied the technology in the mass production of many vehicle models to date⁽²⁾.

Figure 1 shows the configuration of that ASC system. This technology generates engine order sound components synchronized with the engine speed that is acquired from the Controller Area Network (CAN). The sound source signals generated by the ASC Electronic Control Unit (ASC-ECU) are emitted by speakers in the vehicle cabin that are shared with the audio system, and there they combine with cabin interior sounds to become acceleration sounds.

In the case of an xEV, the sound produced by the motor when the EV is operating is comparatively small. New ASC technology capable of generating acceleration sounds suited

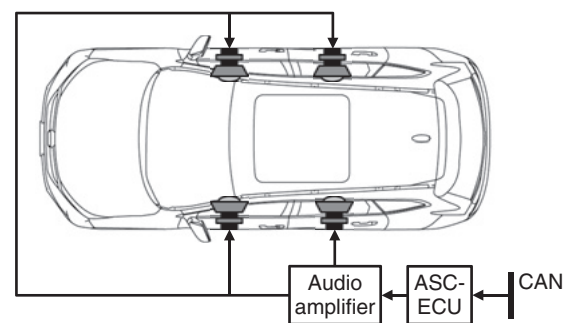


Fig. 1 ASC system configuration

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to the characteristic experience of accelerating seamlessly from initial movement all the way up to high speed was, therefore, considered necessary.

This paper describes the concept for newly developed xEV-ASC technology, provides an overview of the system, and cites cases of its application in vehicles.

2. xEV-ASC Concept

The following three points served as guiding aims in investigating the xEV-ASC:

- (1) Realize a varying sound that is synchronized with vehicle velocity and acceleration
- (2) Realize sounds that can express the acceleration feel typically experienced in driving an EV
- (3) Modulate sounds with a high degree of freedom

2.1. Synchronization with Vehicle Speed

In order to express the acceleration of an EV operating under motor power, it is desirable to vary the quality of the sound that is synchronized with the changing vehicle velocity itself. The speed of the motor, which is the source of driving power when an EV is in operation, is also proportional to the vehicle velocity. The xEV-ASC, therefore, generates acceleration sounds that have the vehicle velocity as a reference signal.

The relationship between the frequency of the acceleration sound and the vehicle velocity is shown in Eq. (1).

$$f(v) = R \times v + F0. \quad (1)$$

Here, v is the vehicle velocity, R is the frequency change rate, and $F0$ expresses the segment on the frequency axis. Figure 2 shows examples of acceleration sound frequency settings according to Eq. (1). Since frequency change rate is one of the factors that influence acceleration feel⁽⁴⁾, the acceleration feel is harder to sense when the frequency change with respect to the vehicle velocity change shown in Ex. 1 of Fig. 2 is gradual. With the higher frequency change rate in Ex. 2, on the other hand, the sound will be at a high frequency when the vehicle velocity is high, making it unpleasant to hear. Under these circumstances, setting the sound to ascend to frequencies that are stepped as in Ex. 3 can make it possible to produce sounds in frequency ranges that will not be unpleasant to the ear while maintaining a

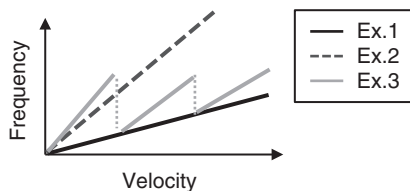


Fig. 2 Typical sound settings according to Eq. (1)

high frequency change rate. However, this will produce sounds like those of a vehicle with automatic or manual transmission (AT/MT), which changes gears, and it cannot readily express the acceleration feel typical of driving an EV with a motor, which accelerates seamlessly from initial movement all the way up to high speed.

For such an ASC that is synchronized with vehicle velocity, therefore, the technical issue is expressing a seamless acceleration feel while keeping the acceleration sounds within a frequency range that will not be unpleasant to the ear.

2.2. Realization of xEV Sound Quality by Application of Shepard Tones

In order to resolve the above technical issue, an approach was conceived that would apply Shepard tones⁽⁵⁾, which are also used for sound effects in music and films.

Shepard tones were devised by R. N. Shepard as sounds consisting of superimposed sine waves that are separated by octave units^{(5), (6)}. When these sounds are reproduced repeatedly, they cause an auditory illusion that makes the pitch seem to be continually rising.

Figure 3 shows the general musical scale and Shepard tones on a keyboard. The progression on the general musical scale, as shown in Fig. 3(a), is toward the right side of the page as the pitch rises by half tones, so that progressing from do (C) by 12 steps ends at C one octave higher. Shepard tones, however, are composed of multiple sounds that are an octave apart, as shown in Fig. 3(b). When these sounds are synchronized and reproduced so as to rise progressively by one octave, then in the case of a single sound, it seems to have risen one octave, but in the case of Shepard tones, it seems to have returned to the original sound. In other words, continuously reproducing a sequence of Shepard tones creates the illusion that the sound is continuing to rise higher.

Figure 4(a) shows a schematic diagram of Shepard tones as a way of understanding this phenomenon. The vertical direction represents the height of the frequency and the circumferential direction represents the height of the musical scale. The red frame marks the chord of C in Shepard tones, and the other tonal scales are arrayed in the circumferential direction. Reproducing each tonal scale

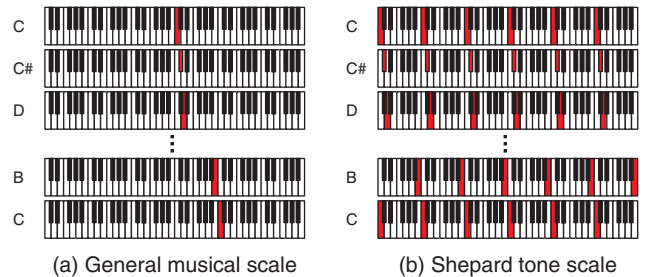


Fig. 3 Musical scale on keyboard for piano

continuously in a counterclockwise direction gives rise to the illusion that the sound is rising continuously like the spiraling arrow shown in the figure. Something that uses a similar illusion is the kind of sign pole shown in Fig. 4(b), which is widely used as a barber's pole or other such advertising sign. In the case of the sign, its rotation causes the visual illusion that the red and blue stripes are continuously rising up.

Reasoning that these Shepard tones could be used to resolve the issue in Section 2.1., development of xEV-ASC technology for generating acceleration sounds by the application of Shepard tones synchronized with vehicle velocity was undertaken.

2.3. Modulation of xEV Sound Quality by Tone Setting

Since Shepard tones are superpositions of sounds that are an octave apart⁽⁵⁾, there are limits to the sound that can be realized. Consequently, the sound from conventional

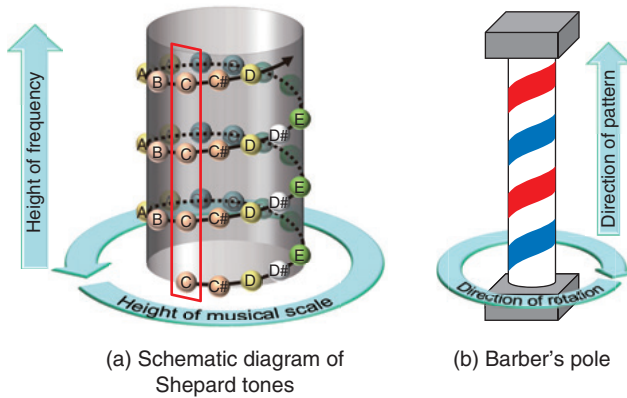


Fig. 4 Shepard tones and barber's pole

Shepard tones alone is insufficient for expressing the various identities of different vehicles.

As a way to enhance the freedom of sound modulation, an approach was conceived for applying the methods for forming chords in music theory to the generation of acceleration sounds while keeping the characteristics of Shepard tones. The set of sine waves that are in octave relationship in the original Shepard tones are defined as the main tones. Tones with a certain frequency ratio with respect to these main tones are defined as sub-tones. It was reasoned that generating multiple sub-tones in addition to main tones would realize a greater abundance of sounds.

3. xEV-ASC System

Figure 5 shows a block diagram of the xEV-ASC system. This system is made up of four modules: the vehicle state acquisition, sound creation, cabin interior acoustic field compensation, and volume control modules. The sound creation module utilizes ASC technology that generates sounds applying newly developed Shepard tones synchronized with the vehicle velocity.

3.1. Vehicle State Acquisition

The vehicle state acquisition module, as shown in Fig. 5, acquires from the CAN the vehicle velocity, accelerator pedal (AP) position, and information on the vehicle dynamic mode (normal, sport, and so on), which are needed to generate the acceleration sounds. The vehicle velocity is also used to perform internal calculation of the vehicle acceleration.

3.2. Sound Creation

The tonal quality of an acceleration sound is determined

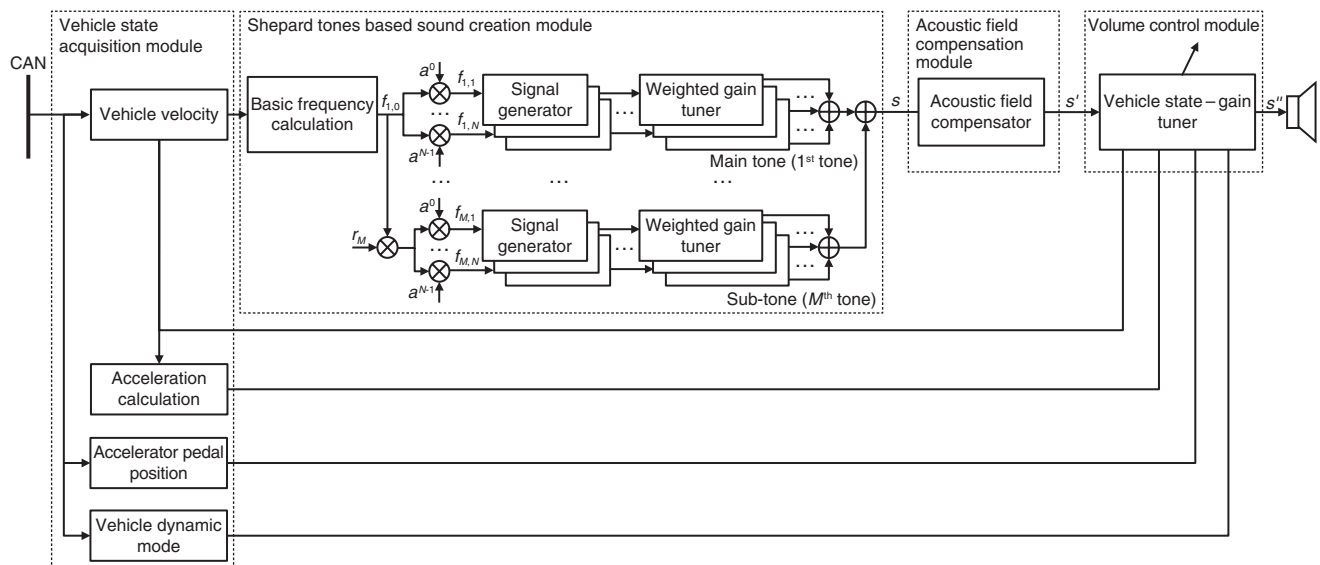


Fig. 5 Block diagram of xEV-ASC system

by its component frequencies and the magnitude of each frequency component. As shown in Fig. 5, the sound creation module calculates the component frequencies based on Shepard tones, generates sine signals for each frequency, and modulates the amplitude of the sine signals. By these three processes, it generates the main tones and sub-tones and configures the sounds.

3.2.1. Creation of main tones

For the creation of main tones, the basic frequency f_0 is calculated as shown in Eqs. (2) through (5).

$$f_0(n) = F_{\min} \times a^{\left(\frac{v(n) - V(n)}{k}\right)}, \quad (2)$$

$$\text{If } f_0(n) \geq F_{\max}, V(n) = v(n), \quad (3)$$

$$\text{Else if } f_0(n) < F_{\min}, V(n) = v(n) - \Delta V(n), \quad (4)$$

$$\text{Else, } V(n) = V(n - 1). \quad (5)$$

Here, n is the discrete time, $F_{\min}$ and $F_{\max}$ are the lower limit frequency and upper limit frequency, respectively, a is the base of the exponential function of vehicle velocity v , V is the vehicle velocity when the basic frequency f_0 reaches the upper limit frequency, and k expresses the frequency change rate modulation coefficient. Of these, k , a , $F_{\min}$, and $F_{\max}$ are control parameters. It can be determined from the above that the basic frequency f_0 varies exponentially between $F_{\min}$ and $F_{\max}$ according to the vehicle velocity. When f_0 exceeds $F_{\max}$ as acceleration occurs, the vehicle velocity v is set to V when $f_0 = F_{\max}$, according to Eq. (3), and this returns f_0 to $F_{\min}$. When f_0 drops below $F_{\min}$ during deceleration, V is set to $v - \Delta V$ in order to bring f_0 to $F_{\max}$. Here, ΔV expresses the amount of change in the vehicle velocity when f_0 rises from $F_{\min}$ to $F_{\max}$, and it can be calculated as shown in Eq. (6).

$$\Delta V = k \log_a \frac{F_{\max}}{F_{\min}}. \quad (6)$$

ΔV is calculated using k , a , $F_{\min}$, and $F_{\max}$, which are decided in advance as control parameters.

The N th component frequency of the main tones is calculated from f_0 , as shown in Eqs. (7) and (8).

$$f_N(n) = f_0 \times a^{N-1}, \quad (7)$$

$$\text{If } f_N(n) \geq F_{\max}, f_N(n) = f_N(n) \times \frac{F_{\min}}{F_{\max}}. \quad (8)$$

The number of necessary component frequencies $N_{\max}$ is determined by a , $F_{\min}$, and $F_{\max}$.

$$N_{\max} = \log_a \frac{F_{\max}}{F_{\min}}. \quad (9)$$

According to Eqs. (7) and (8), the ratio of any two adjoining component frequencies will consistently be the constant a . When $a = 2$, the component frequencies of the acceleration sounds are the original Shepard tones, which consistently maintain an octave relationship, producing a

harmonious sound. Figure 6 shows an example of Shepard tone frequency components that include six components calculated by Eqs. (2) to (8).

The sine signal s_N for each frequency component is generated by the signal generator according to the respective frequency. The magnitude of the respective sine waves is determined by modulating the two weighted gains shown in Fig. 7.

$G_S(f)$ is a weighted gain for the purpose of causing auditory illusion by means of the Shepard tones by causing the low-frequency and high-frequency sounds in the range between $F_{\min}$ and $F_{\max}$ to fade in and fade out smoothly. Figure 8 shows an example of this configuration. By the use of $G_S(f)$ and Eqs. (2) through (8), the acceleration sound that has the Shepard tones characteristics shown in

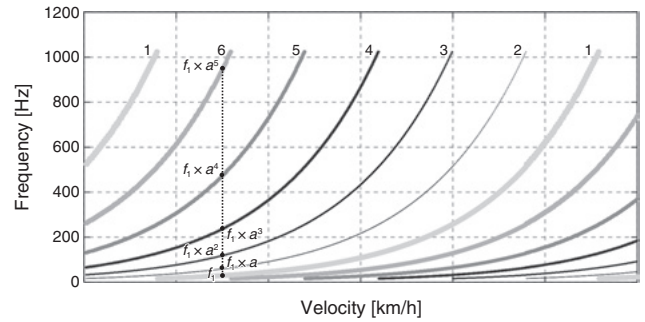


Fig. 6 Example of calculated frequencies

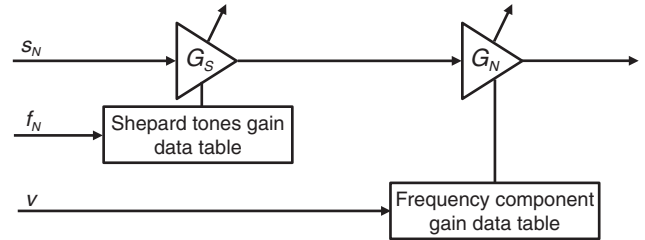


Fig. 7 Block diagram of weighted gain tuner

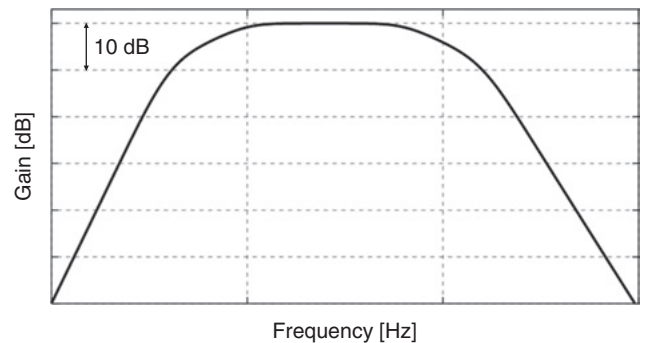


Fig. 8 Example of Shepard tones gain $G_S(f)$

Fig. 9 can be generated in synchronization with the vehicle velocity.

$G_N(v)$ is the weighted gain of each frequency component that is based on vehicle velocity. As shown by the configuration example in Fig. 10, the sound can be modulated by changing the ratio of frequency component magnitudes according to the vehicle velocity.

3.2.2. Creation of sub-tones

In creating sub-tones, when the ratio between the basic frequencies of the M th sub-tone and the main tone is set to r_M , the component frequency $f_{M,N}$ can be calculated as shown in Eq. (10).

$$f_{M,N}(n) = r_M \times f_{1,0}(n) \times a^{N-1}. \quad (10)$$

It is possible to set r_M on the basis, for example, of music theory⁽⁷⁾. Table 1 shows the triads, which are the basic chords made up of three sounds together with the impressions⁽⁸⁾ of the sounds that are expressed by those triads. Major and minor triads can express bright and dark sounds. It is said that suspended triads can give an impression of the fantastic. These can be configured for use according to the characteristics of the vehicle. A diminished triad is said to have an unstable sound, which may conceivably have uses when encouraging caution. When configuring a sound with three tones based on a major triad

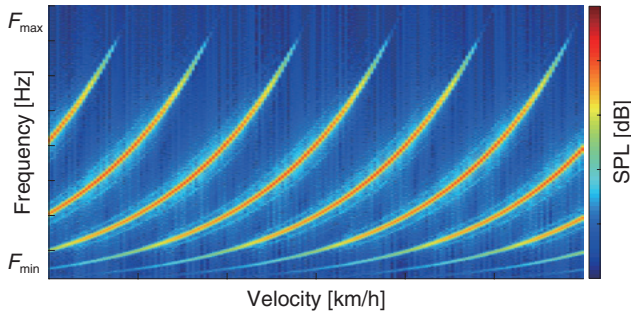


Fig. 9 Example of Shepard tones based acceleration sound

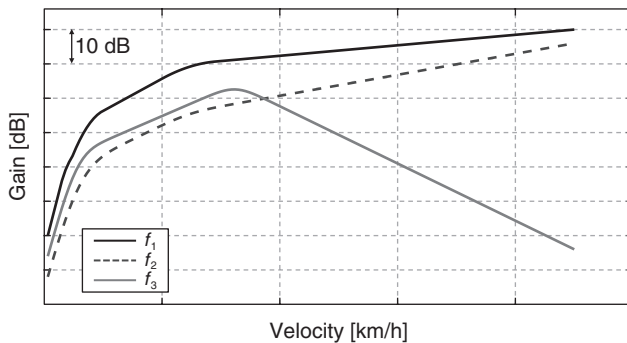


Fig. 10 Example of frequency component gain $G_N(v)$

Table 1 Typical triads and impressions of triads

Chord type	Frequency ratio	Impression
Major	1:1.25:1.5	Bright/Pleasant
Minor	1:1.2:1.5	Dark/Sad
Suspended	1:1.33:1.5	Fantastic
Diminished	1:1.2:1.42	Unstable/Transient
Augmented	1:1.25:1.6	Unstable/Transient

to give a bright impression, for instance, this can be done by setting the frequency ratio $r_1:r_2:r_3$ of the main tones and two sub-tones to 1:1.25:1.5.

The signal s that is the output of the sound creation module is calculated by adding together the various frequency component signals for each tone, as in Eq. (11). In this way, it is possible to assign multiple sounds that have freely selectable frequency ratios.

$$s(n) = \sum_{M=1}^{ALL} \sum_{N=1}^{ALL} G_N(v(n)) \times G_S(f_{M,N}(n)) \times G_C(f_{M,N}(n)) \times s_{M,N}(n). \quad (11)$$

3.3. Cabin Interior Acoustic Field Compensation

As indicated by the gray line in Fig. 11, the gain characteristics of the acoustic response from the speaker to the vehicle occupant's head as influenced by the acoustic field inside the vehicle cabin have peaks and valleys. The acceleration sounds transmitted to vehicle occupants vary in the magnitude of the sound components, depending on their frequencies, and thus sounds cannot be guaranteed to be exactly as configured in advance. In order to realize the acceleration sound quality, as configured, at the vehicle occupant's location, therefore, the magnitude of each frequency component is compensated by using the inverse $G_C(f)$ of the cabin interior acoustic response gain characteristics, indicated by the black line in Fig. 11.

3.4. Volume Control

In order to achieve a balance between quietness when cruising and acceleration feel when accelerating, as well as to produce acceleration sounds that are coordinated with the behavior of the vehicle and operations performed by vehicle

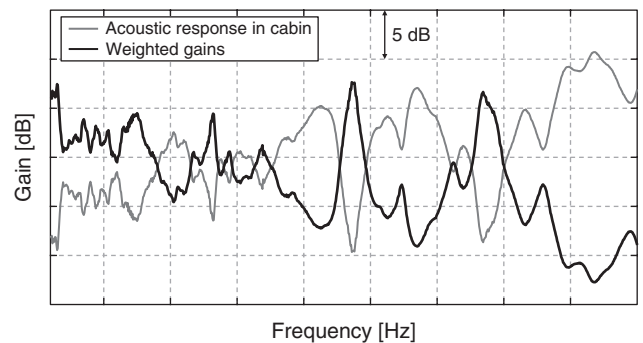


Fig. 11 Example of acoustic compensation gain $G_C(f)$

occupants, a means is provided to modulate the overall volume of the acceleration sounds according to the vehicle's velocity, acceleration, and AP position. By arranging the system so that the acceleration sound volume can be set for each of the vehicle dynamic modes selected by vehicle occupants, such as normal, sport, and so on, the system can also be switched between cabin interior sound settings that emphasize quietness or that emphasize acceleration feel, depending on the vehicle dynamic mode.

Figures 12 through 14 show examples of settings for vehicle velocity gain $G_V(v)$, acceleration gain $G_{Acc}(\Delta v)$,

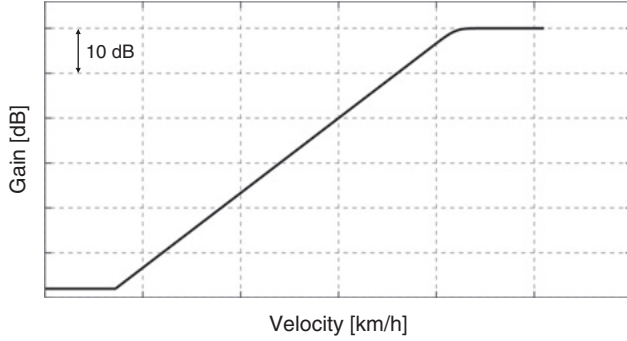


Fig. 12 Example of velocity gain $G_V(v)$

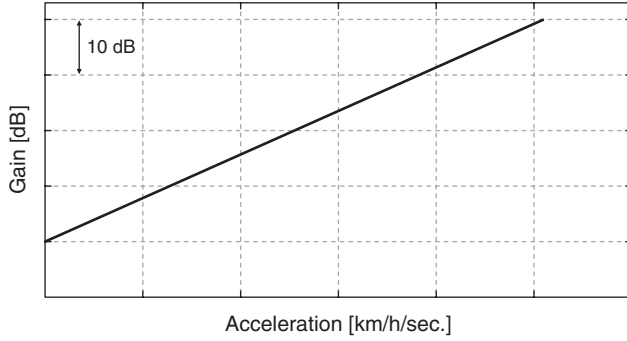


Fig. 13 Example of acceleration gain $G_{Acc}(\Delta v)$

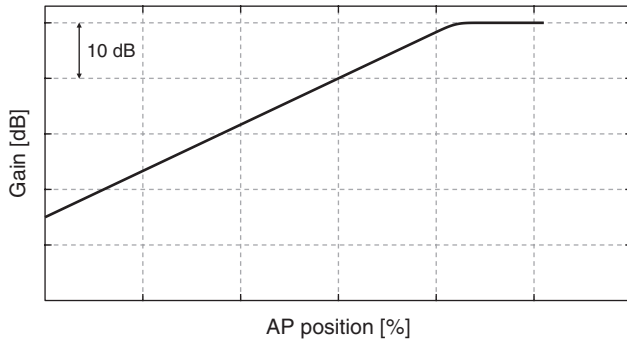


Fig. 14 Example of accelerator pedal position gain $G_{AP}(p)$

Table 2 Example of vehicle dynamic mode gain

Vehicle dynamic mode	Dynamic mode gain $G_M(m)$
Comfort	-90 dB
Normal	0 dB
Sport	+6 dB
...	...

and AP position gain $G_{AP}(p)$, respectively. These can be set so that the sound volume increases with increases in the vehicle velocity and acceleration and with the AP opening. Table 2 shows examples of settings for vehicle dynamic mode gain $G_M(m)$. These can be set so that in comfort mode, no sound is output, while in sport mode, the sound volume is set to a high level to emphasize the acceleration feel.

The acceleration sound signal s'' is output from the speakers after first undergoing volume control as shown in Eq. (12) with respect to signal s' , which has undergone acoustic field compensation.

$$s''(n) = s'(n) \times G_M(m(n)) \times [\alpha \times G_A(\Delta v(n)) + (1 - \alpha) \times G_V(v(n)) \times G_{AP}(p(n))]. \quad (12)$$

Here, α is a parameter that modulates the ratio of acceleration gain and AP position gain. It satisfies the condition $0 \leq \alpha \leq 1$.

4. Cases of Application in Vehicles

Here, the case of application of this system in an SUV Plug-in Hybrid EV (PHEV) for the China market that is scheduled to go on sale in 2021 will be introduced. The system is configured in the same way shown in Fig. 2. The ASC-ECU generates acceleration sound signals based on vehicle information acquired from the CAN. The signals are emitted in the vehicle cabin from speakers that are shared with the audio system. In this way, the system acts to enhance the acceleration feel of the subject vehicle during EV operation.

4.1. System Settings

The first item was to investigate how to set the sub-tones. A number of settings based on the triads in Table 1 were tried, and eventually the configuration of major triad with bright sounds was adopted. As stated in Clause 3.2.2., the ratio was set as $r_1:r_2:r_3 = 1:1.25:1.5$ with the aim of creating a bright acceleration sound. Then, on the premise that this will be the sound, the parameters for modulating the sound and volume were tuned by repeated testing in an actual vehicle.

Next, the range of frequencies was investigated. Since the upper limit frequency expresses the enjoyable quality of EV driving, it was reasoned that this frequency should be

made somewhat higher. From the experience of ASC tuning in conventional engine-powered vehicles, it was reasoned that the high frequency around the 8th-order sound of a four-cylinder, four-cycle engine would be needed. Since that 8th-order sound was 800 Hz at 6000 rpm, the upper limit frequency was set to $F_{\max} = 800$ Hz. Based on the lower limit frequency that can be reproduced by speakers, the lower limit frequency was set to $F_{\min} = 50$ Hz. As a result, there were four main tones generated at the same vehicle velocity according to parameters a , $F_{\min}$, and $F_{\max}$ and Eq. (9).

Regarding parameters k and a , which are used to modulate the frequency change rate, these were tuned to match them to the acceleration performance of the subject vehicle. They were set to $k = 25$ km/h and $a = 2$. It is apparent from Eq. (6) that a single sine wave is generated so as to repeat at a frequency between $F_{\min}$ and $F_{\max}$ at intervals of $\Delta V = 100$ km/h. Since one tone is composed of four sine waves, this also means that the frequency components of the tone are repeated each 25 km/h.

In order to make the various frequency components fade in and fade out smoothly, the gain $G_S(f)$ setting shown in Fig. 8 was used. The gain $G_N(v)$ of each frequency component was set as shown in Fig. 15 so as to emphasize the linearity of acceleration sounds and put the gain of each frequency component at the same value. Given these conditions, the gain was set to rise with increasing vehicle velocity.

The volume control was configured to coordinate the acceleration sound volume with the acceleration of the vehicle and AP operation by vehicle occupants. The vehicle velocity gain $G_V(v)$ was set to 0 dB throughout the entire vehicle velocity range. The acceleration gain $G_{Acc}(\Delta v)$ and AP position gain $G_{AP}(p)$ were set as shown in Figs. 13 and 14 so that the volume would rise with increases in acceleration and with greater AP opening by vehicle occupants. In order to emphasize quietness when driving in normal mode while also providing a strong acceleration feel during acceleration in sport mode, the vehicle dynamic mode gain $G_M(m)$ was set to deliver

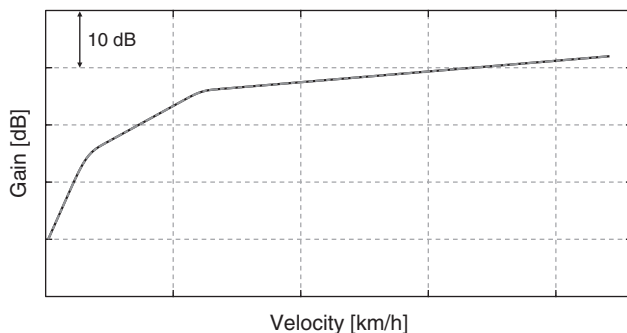
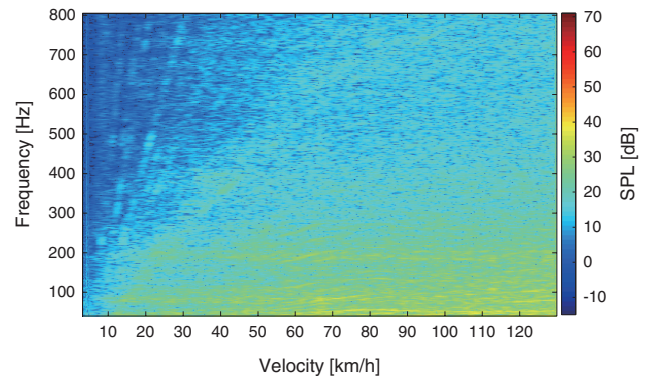


Fig. 15 Frequency component gain $G_N(v)$ for test car

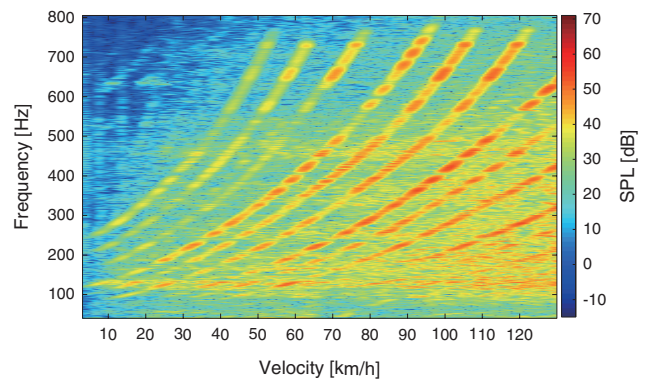
acceleration sounds that would be felt when driving in sport mode.

4.2. xEV-ASC Control Effects

Figure 16 shows spectrograms of cabin interior sound with and without the xEV-ASC system. When without the xEV-ASC system, there are fewer sound components that change frequency as the vehicle velocity increases. When with the xEV-ASC system, on the other hand, acceleration sounds with Shepard tone characteristics, meaning they are repeated every 25 km/h between $F_{\min}$ and $F_{\max}$, are generated in synchronization with vehicle velocity. Test rides of the vehicle equipped with the xEV-ASC system were conducted in-house. The results confirmed that the xEV-ASC system can enhance the acceleration feel that vehicle occupants receive when accelerating during EV operation of the vehicle. The xEV-ASC system is capable of generating acceleration sounds with a quality that matches the characteristics of EV driving, which delivers a seamless acceleration feel. It was successfully confirmed that the system can be used to produce distinctive xEV acceleration sounds.



(a) Without xEV-ASC system



(b) With xEV-ASC system

Fig. 16 Interior sound spectrogram of test car

5. Conclusion

This paper reported on newly developed xEV-ASC technology. This technology uses the concept of Shepard tones to generate acceleration sounds that are synchronized with vehicle velocity, thereby realizing a sound that can express the seamless acceleration feel experienced during motor-powered EV operation. The technology further achieves sound modulation with a high degree of freedom by the configuration of main tones and sub-tones. This technology was also applied, and its effectiveness was confirmed, in an SUV PHEV for the China market that is scheduled to go on sale in 2021.

For the xEV of the future, this technology is thought to have the potential to become an important element of the technologies that will be used to help form a vehicle's identity.

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