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Study on Noise Control Effect of Secondary Sound Source Distribution in Vehicle Interior

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Abstract. In order to analyze impacts of secondary sound source distribution on vehicle interior noise, the finite element model of a vehicle is built. The optimal distribution of secondary sound source is obtained from an input-output relationship between source locations and sound pressure level, noise characteristics and noise reduction. The results show that the noise reduction effect is the best when the secondary sound source is placed on the side wall of the driver and crew, and the noise reduction effect is more than 7.4dB. When the secondary sound source cloth is placed above the head of the driver and crew, the noise reduction effect is the second. When the secondary sound source is placed at the bottom of the chassis, the noise reduction effect is the worst. When the secondary sound source is placed near the head of the main driver's seat, the noise reduction effect of the local space near the head of the main driver's seat can reach more than 10 dB. It is shown that placing secondary sound sources in the vehicle interior can effectively reduce the vehicle interior noise and improve the sound quality of the whole vehicle.

Keywords: vehicle interior noise, active noise control, acoustical fem, secondary sound resource

1 Introduction

Automobile interior noise not only seriously damages the hearing system of drivers, but also compromises the comfort ability of passengers [1]. Therefore, reducing vehicle interior noise is a research subject of practical application significance.

Passive and active noise control techniques are commonly used in noise control. In general, the passive control technology can reduce the interior noise by adding special material, which has significant effects on medium and high frequency noise reduction [2], but not low frequency noise. Active noise control technology is to reduce the noise through the principle of acoustic cancellation.

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With the development of electronic technology, more and more active noise control techniques have been applied to noise control in enclosed space [3-6]. Compared with passive noise control system, active noise control system is smaller in size, lighter in weight and favored by automobile manufacturers [7-8]. However, how to deploy active noise control system to effectively reduce the noise in the limited space is a hot topic for scholars.

Based on the second-order sequence algorithm, Yang et al. calculated the optimal placement of secondary sources for the acoustic structure model with rigid and elastic boundaries [9]. In this paper, genetic algorithm is introduced into Tsahalis, and the optimal solution of secondary source location is obtained by neglecting the interaction between location and sound intensity [10]. Based on several genetic algorithms, Hansen et al. studied the influence of the position of the secondary source on the noise control performance [11] in the active noise control system. Guo et al. improved the Fuzzy Control Algorithm and applied it to the active noise control in the car interior [12]. In the active sound field of multi-input and multi-output rectangular Shell [13], the distribution of secondary sound sources is analyzed by Montazeri et al. Wang et al used genetic algorithm to optimize the secondary source location and applied it to the effective noise control in the actual transformer working environment [14]. Li HY et al [15] applied genetic algorithm to optimize the layout of sound source, and solved the layout optimization problem of active noise suppression system in small damping rectangular acoustic structure. Chen Kean et al [16] integrated secondary sound source, reference sensor, error sensor and controller in one plane, and designed an active noise control system model, the number and position distribution of secondary sources which can effectively suppress noise are discussed. Taking three-dimensional rectangular space as an example, an acoustic finite element model is established by using SYSNOISE software. The noise reduction of the system when the secondary source is placed in different positions is analyzed, and the optimal placement location of the secondary source is obtained. Ma TX et al [17]. constructed a finite element model of a car interior enclosed space using LMS virtual Lab. The acoustic-vibration coupling mode of the model is solved by lab acoustics, and the sound field distribution in the closed space is analyzed. The sound attenuation simulation experiment of the closed space is carried out by using two monopole sound sources and a good global sound attenuation effect is obtained. In this paper, an optimization method of secondary sound source layout based on Monte Carlo method simulation is presented, Zhang WQ et al [18]. which makes the ANC system with optimized secondary sound source layout more effective than the optimized system. DF Wang et al [19]. The influence of the location, amplitude and phase of the secondary sound source on the sound field characteristics is studied by using the principle of minimization of the space sound potential energy. Most of the above-mentioned scholars have studied [20] the placement of secondary sound sources for a rectangular or cylindrical space acoustic structure model. In fact, the interior space of a car is not exactly a rectangle. Even if the secondary sound source is placed in a reasonable position in theory, it will be affected by the body structure and interior decoration when it is actually placed, making it very difficult to put a secondary sound source inside the car. Therefore, according to the body structure and noise level, it is an urgent task to design the parameters and placement of secondary noise sources for automobile interior noise control.

This article is a reverse engineering study of a domestic car using LMS virtual Lab. The acoustic finite element method is used to calculate the sound pressure level of the sound field in the sound cavity space of the whole vehicle. The effect of the location and frequency of the secondary sound source on the noise cancellation is discussed, the optimal secondary sound source location and frequency range are determined from the effect of the space sound field, and then the optimal secondary sound source location and parameters are found in the limited indoor space, an active noise control system is established in the whole and part of the vehicle interior.

2 Numerical Model and Method

2.1 Sound Pressure and Sound Pressure Level

Active noise control technology is an electro-acoustic technology based on acoustics. In order to realize active noise reduction, the active noise control technology must be theoretically analyzed using the basic principles of acoustics. Sound pressure is the change in atmospheric pressure caused by the disturbance of sound waves. It is a function of position and time in the 3D and can be used to measure the strength of sound waves. Because the sound pressure is easy to measure, and the parameters such as particle velocity and sound pressure level can be obtained indirectly through the sound pressure value, the RMS value of the instantaneous sound pressure over a period of time is called the effective sound pressure, namely:

$$p_e = \sqrt{\frac{1}{T}\int_0^T P^2 dt} \tag{1}$$

Where, T is the time interval.

The primary perception of sound waves by the human ear is more proportional to the logarithm of the amplitude and can be described by the sound pressure (in dB):

$$SPL = 20\log\frac{p_e}{p_{ref}} \tag{2}$$

Where, p_{ref} is the reference pressure, $2\times10^{-5}\,Pa$.

The calculation formula of the average sound pressure level is:

$$SPL = \frac{1}{N}\sum_{i=1}^{N} SPL_i \tag{3}$$

Where, i represents the number of IO points at the sound pressure observation point.

2.2 Finite Element Model of Automobile Interior

In order to analyze the interior noise distribution and the deployment strategy of the secondary sound source, a finite element model of the vehicle structure is established, because tetrahedral Mesh can discretize the model with complex boundary surface, and it is faster than hexahedral Mesh, tetrahedral Mesh is used to discretize the model. The number of tetrahedral meshes generated is 7650, because the interior engine noise is the main noise source, and it is mainly distributed in 50Hz ~800Hz, and the Mesh length should be less than 1/6 wavelength in order to improve accuracy, the maximum unit size is 7 cm, the acoustic medium condition is set to normal air temperature and pressure, speed of sound is 340 m/s, and the mass density is 1.225 Kg/m^3. The position of the primary sound source is located near the automobile chassis engine, as shown in Fig. 1. The secondary source parameters used in this paper are shown in Table 1.

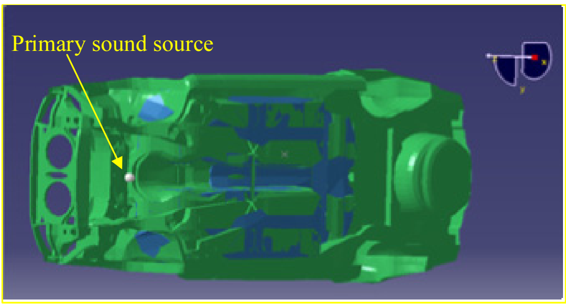

Fig. 1. Primary sound source location map

Table 1. Secondary sound source parameters

Frequency/(Hz)	Amplitude/(kg/s2)	Phase/(deg)
100	0.400	86.82
200	0.064	-6.35
300	0.004	-99.53

Considering that the interior noise mainly affects the driver's comfortability, 40 IO sound pressure monitoring points are set up near the head of the main driver's seat, as shown in Fig. 2. The IO point is labeled as 1:40, which is used to analyze the noise level at the driver's position where only the primary sound source impacts on the driver and to discuss the influence of the sound source frequency on the noise control effect.

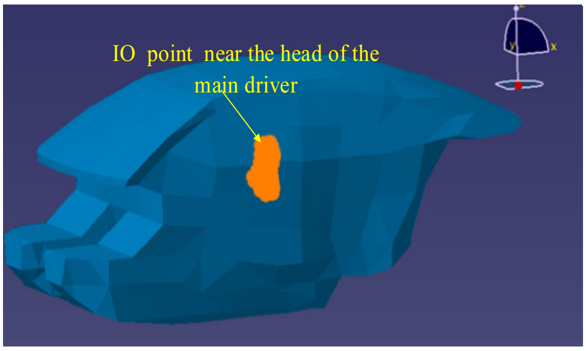

Fig. 2. Schematic diagram of the IO point position near the head of the main driver

2.3 Distribution and Characteristics of Sound field in Automobile Interior

For the convenience of calculation, the interior surface of the car is set as a rigid wall, and the seat modeled by rigid material. When the primary source frequency is 100Hz, the distribution of sound pressure level in the vehicle interior is calculated, the corresponding sound pressure-level cloud map is shown in Fig. 3.

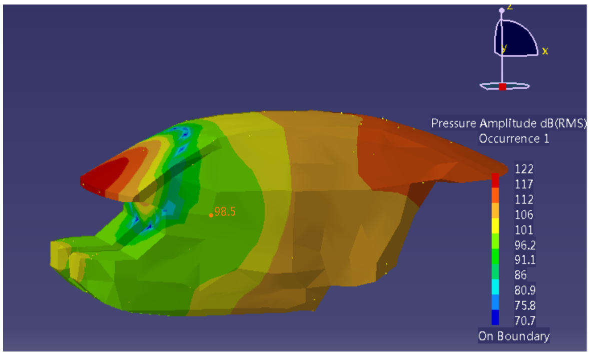

Fig. 3. Sound pressure level cloud of primary source

As shown in Fig. 3, the noise pressure level in the engine is between 70.7 dB and 122 dB in the interior of the car body, the left and right sides of the car body are symmetrical. In addition, the noise pressure level distribution from the front to the rear part of the car body shows a step distribution.

In order to further calculate the magnitude of the sound pressure level at the monitoring point. According to the Acoustic response calculated in Fig. 3, 40 IO points defined as the sound pressure observation points are used to calculate the sound pressure level at the IO points, the result is shown in Fig. 4.

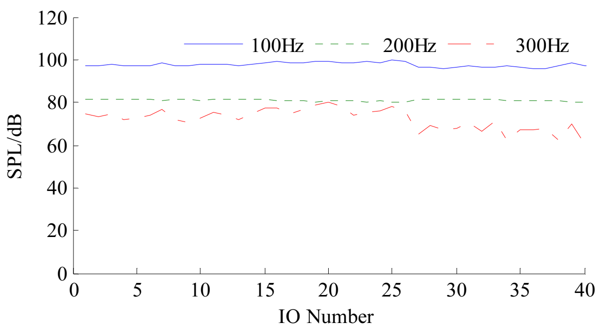

Fig. 4. Sound pressure level at the IO point of the human head when the primary sound source acts alone

As can be seen from Fig. 4, the sound pressure levels of 100Hz, 200Hz and 300Hz at the pressure monitoring point IO are 95.6dB~99.6 dB, 79.0dB~81.6dB, 60.3dB~79.8dB, respectively when the primary source acted alone, the sound pressure level at 100 Hz is greater than that of 200 Hz and 300 Hz, which is consistent with the characteristic that low-frequency noise is greater than high-frequency noise.

Similar to the primary sound source, a secondary sound source is set up in the finite element model of the whole vehicle because the sound waves emitted by the secondary sound source have to interact with the sound waves emitted by the primary sound source in order to achieve a certain noise reduction effect. Therefore, this article places it near the head position of the main driving seat, as shown in Fig. 5.

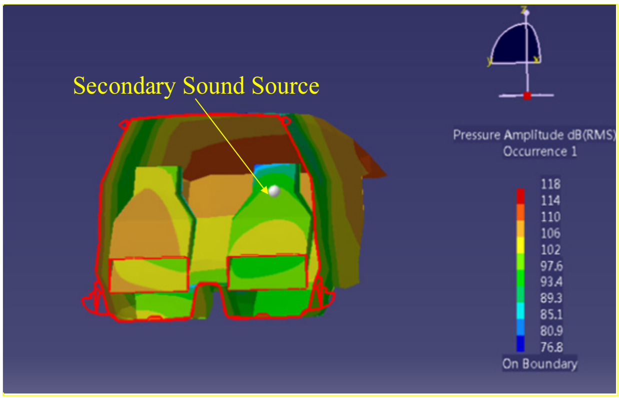

Fig. 5. Schematic diagram of secondary sound source location

In order to observe the noise pressure level and the range of fluctuation at the probes after the secondary sound source is added, the Acoustic response is calculated according to the position of the secondary sound source in Fig. 5. Meanwhile, the defined 40 IO points in Fig. 2 are taken as sound pressure observation points, and the IO point sound pressure level is calculated, and the result is shown in Fig. 6.

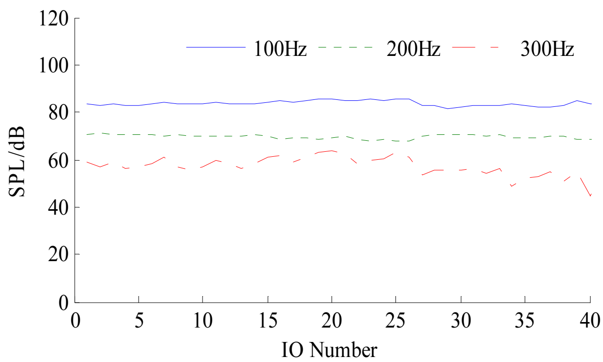

Fig. 6. Sound pressure level at IO point after adding secondary source

As demonstrated in Fig. 6, ranges of sound pressure level at 100 Hz, 200 Hz and 300 Hz are 81.7 dB~85.7 dB, 66.6 dB~71.1 dB and 44.6 dB~64.0 dB, respectively. Compared with Fig. 4 of the pressure monitoring point when the primary source acts alone, the noise pressure level is obviously lower.

2.4 Evaluation Method of Noise Reduction Effect

In order to analyze the noise reduction effect of the secondary sound source near the head of the rear driver's seat, it can be determined according to the difference between the average sound pressure level SPL_1 when only the primary sound source acts and the average sound pressure level SPL_2 when the primary and secondary sound sources act together after adding the secondary sound source, then the noise reduction amount can be expressed as $\Delta E = SPL_1 - SPL_2$, and the calculation result is shown in Table 2.

Table 2. Noise reduction at IO point in driver's head

Frequency(Hz)	SPL_1(dB)	SPL_2(dB)	ΔE(dB)
100Hz	97.6	83.7	13.9
200Hz	80.8	69.4	11.4
300Hz	71.7	60.9	10.8

Table 2 shows that the average sound pressure level in the cab is 83.7 dB at 100 Hz, 69.4 dB at 200 Hz, and 60.9 dB at 300 Hz, respectively. After the secondary sound source is added near the head of the main driver's seat, the noise reduction at 100 Hz, 200 Hz and 300 Hz was 13.9 dB, 11.4 dB and 10.9 dB, respectively.

3 Simulation of Noise Reduction in the Interior Space of Automobile

Vehicle Interior space is a closed cavity system [21] with bounded uncertainty. Therefore, the distribution of the sound field calculated by the acoustic finite element software is extremely complex, and it is impossible to reduce every part of the vehicle noise by active noise control. Even if the secondary sound source is placed at the most reasonable location in theory, it would be affected by the body structure and interior decoration. Additionally, no space has been reserved for the secondary sound source in existing vehicles, which makes it very difficult to include the secondary sound source in the vehicle's active control system.

In this paper, three different secondary sound source distribution schemes are proposed according to the body shape of car, and four secondary sound sources are used in all three schemes. The three layout schemes are designed as follows: the top of the car directly above the head of the driver, the side wall of the car and the head of the driver are at the same height and symmetrical position, and the chassis of the car is directly opposite to the head of the driver. In order to observe the sound pressure distribution in the whole car chamber, 250 I/O points are defined and labeled as 1: 250 sound pressure monitoring points. The sound pressure level distribution in the whole car chamber can be obtained by calculating the acoustic response. The position of Io points is shown in Fig. 7 below, the distribution of I/O sound pressure level in an automobile room with a primary sound source acting alone is shown in Fig. 8.

In Fig. 7, the defined I/O points are distributed throughout the interior, so that the output of the IO points can reflect the distribution of the sound pressure level in the interior of the car.

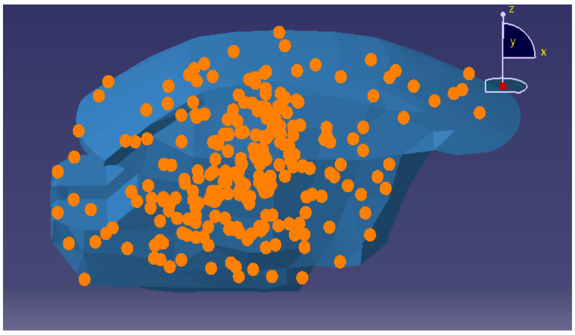

Fig. 7. Schematic diagram of the I/O point in the car

As can be seen from Fig. 8, when only the primary sound source is present, ranges of sound pressure level at 100 Hz, 200 Hz, 300 Hz are 62.1 dB to 116.1 dB, 17.5 dB to 99.4 dB, 21.9 dB to 93.6 dB, the fluctuation of sound pressure level at IO point is relatively large at 100Hz, 200Hz and 300Hz,. Note that the sound pressure level is unevenly distributed in the car room.

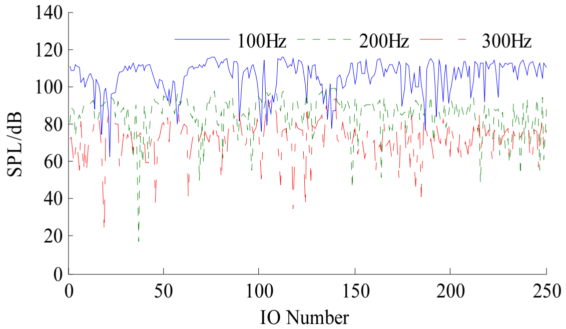

Fig. 8. Sound pressure level of IO point in vehicle indoor when primary sound source acts

3.1 Secondary Sound Source Deployment Optimization

(1) The following explores the distribution of the sound pressure level of the IO point in the car room when the secondary sound source is placed in different locations. The secondary sound source is defined in the car roof location, the serial number is marked 1-4, and the four secondary sound source parameters are set as shown in Table 3. This design method is scheme 1.

Secondary sound source location settings:

Secondary sound source	x(cm)	y(cm)	z(cm)
1	161.2	-37.4	108.2
2	161.2	37.4	108.2
3	225.6	-38.0	103.3
4	225.6	38.0	103.3

Table 3. Secondary sound source parameters at the ceiling of the vehicle

Secondary sound source	Frequency/(Hz)	Amplitude/(kg/s2)	Phase/(deg)
1	100	0.100	48.71
	200	0.016	-82.59
	300	0.010	146.12
2	100	0.100	48.71
	200	0.016	-82.59
	300	0.010	146.12
3	100	0.100	-2.12
	200	0.016	175.76
	300	0.010	-6.35
4	100	0.100	-2.12
	200	0.016	175.76
	300	0.010	-6.35

To calculate the acoustic response in the vehicle compartment, the acoustic pressure-level cloud map is shown in Fig. 9, and the sound pressure level of I/O point is shown in Fig. 10.

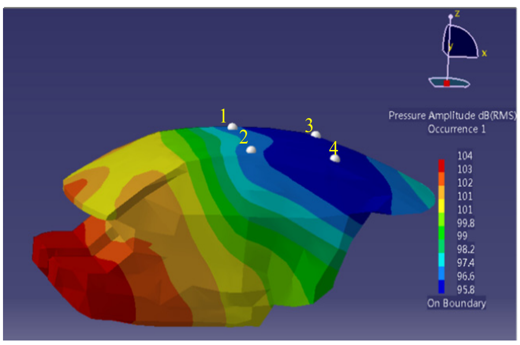

Fig. 9. Sound pressure level cloud image after ceiling adds secondary sound source

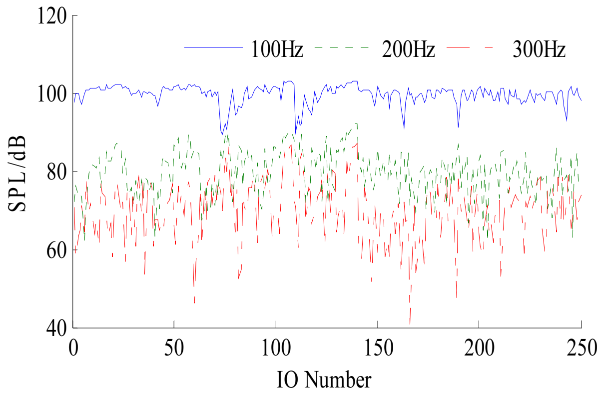

Fig. 10. Sound pressure level of the IO point in vehicle indoor rafter ceiling adds secondary sound source

After adding a secondary sound source to the car roof position, as can be seen from Fig. 9, the sound pressure level range near the secondary sound source is 95.8 dB~97.4 dB. According to the cloud map, the sound pressure level is gradually reduced from 104 dB at the front to 96 dB at the rear of the room.

As can be seen from Fig. 10, the sound pressure level range is 89.2 dB-103.1 dB, 61.9 dB-92.2 dB, 40.5 dB-86.8 dB at 100 Hz, 200 Hz, 300 Hz, and noise is significantly reduced compared with the primary sound source alone. The fluctuation of sound pressure level at IO point of noise at 100 Hz is remarkably reduced, while that at IO point of noise at 200 Hz and 300 Hz is slightly reduced.

(2) The secondary sound source is defined at the sidewall of the car, the serial number is marked 1-4, and the four secondary sound source parameters are shown in Table 4. This design method is scheme 2.

Table 4. Secondary sound source parameters at the sidewall of the vehicle

Secondary sound source	Frequency/(Hz)	Amplitude/(kg/s2)	Phase/(deg)
1	100	0.100	58.24
	200	0.016	-63.53
	300	0.010	174.71
2	100	0.100	58.24
	200	0.016	-63.53
	300	0.010	174.71
3	100	0.100	2.12
	200	0.016	-175.76
	300	0.010	6.35
4	100	0.100	2.12
	200	0.016	-175.76
	300	0.010	6.35

Secondary sound source locations:

Secondary sound source	x(cm)	y(cm)	z(cm)
1	147.6	68.1	68.8
2	147.6	-68.1	68.8
3	208.1	65.3	66.9
4	208.1	-65.3	66.9

Four secondary sound sources are symmetrically distributed on the side wall of the car at the same height as the occupant's head. Calculate the acoustic response of the whole space in the car room. The cloud map of sound pressure level is shown in Fig. 11, and the sound pressure level of IO point is shown in Fig. 12.

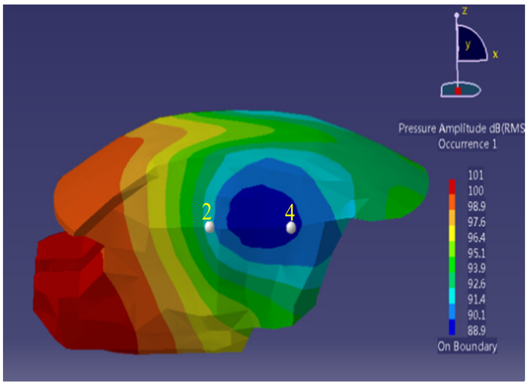

Fig. 11. Sound pressure level cloud image after sidewall adds secondary sound source

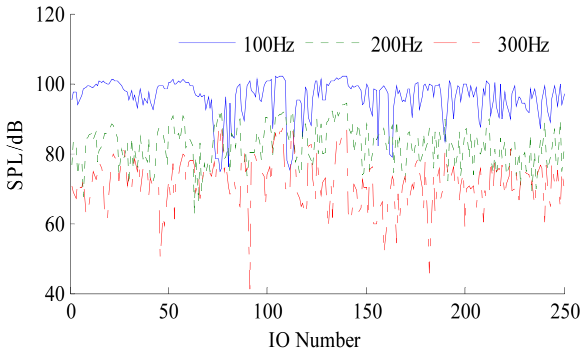

Fig. 12. Sound pressure level of the IO point in vehicle indoor rafter sidewall adds secondary sound source

After adding secondary sound source in the sidewall of the car, as can be seen from Fig. 11, the sound pressure level range near the secondary sound source is 88.9 dB-92.6 dB. The noise is significantly reduced compared with the primary sound source alone. The color distribution of the cloud graph can be seen, the sound pressure level is gradually reduced from the front to the rear end of the car room and the symmetrical distribution is on the left and right. The sound pressure level of the front of the car is 101 dB, a minimum of 89 dB near secondary sound sources and 93 dB at the rear of the vehicle.

As can be seen from Fig. 12, with the addition of secondary sound sources on the sidewalls, the sound pressure level range is 74.8 dB-102.1 dB, 47.5 dB-89.2 dB, 39.4 dB-84.3 dB at 100 Hz, 200 Hz, 300 Hz, compared with the primary sound source, the fluctuation of sound pressure level of 100Hz, 200Hz and 300Hz noise at IO point is reduced.

(3) The secondary sound source is positioned at the bottom of the car, the serial number is marked 1-4, and the four secondary sound source parameters are shown in Table 5. This design method is scheme 3.

Table 5. Secondary sound source parameters at the bottom of the vehicle

Secondary sound source	Frequency/(Hz)	Amplitude/(kg/s2)	Phase/(deg)
	100	0.100	-67.76
1	200	0.016	44.47
	300	0.010	156.71
	100	0.100	-67.76
2	200	0.016	44.47
	300	0.010	156.71
	100	0.100	44.47
3	200	0.016	-167.29
	300	0.010	19.06
4	100	0.100	44.47
	200	0.016	-167.29
	300	0.010	19.06

Secondary sound source location settings:

Secondary sound source	x(cm)	y(cm)	z(cm)
1	135.8	-40.2	-13.4
2	135.8	40.2	-13.4
3	217.5	-43.0	7.5
4	217.5	43.0	7.5

Four secondary sound sources are placed in the chassis position of the car, facing the crew head. Calculate the acoustic response of the car's full space, the acoustic pressure-level cloud map is shown in Fig. 13, and the IO point sound pressure level is shown in Fig. 14.

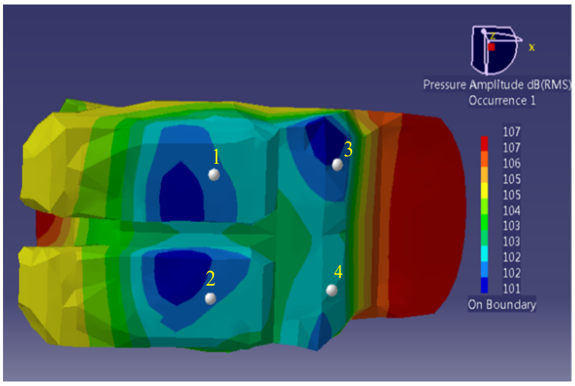

Fig. 13. Sound pressure level cloud image after bottom adds secondary sound source

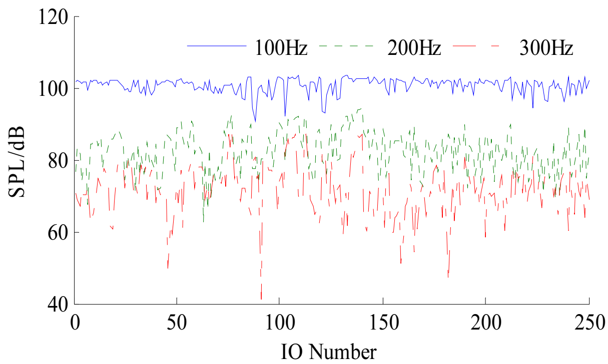

Fig. 14. Sound pressure level of the IO point in vehicle indoor rafter bottom adds secondary sound source

After adding a secondary sound source to the bottom of the car, Fig. 13 shows that the noise pressure level near the secondary sound source is around 101 dB~102 dB. The color distribution of the cloud map can be seen, the sound pressure level near the secondary sound source is less than other positions of the car, the sound pressure level is equal at the front and rear. Note that sound pressure level in the whole car room is similar.

3.2 Full Space Noise Reduction Effect

After adding secondary sound source at the bottom, as shown in Fig. 14, the noise sound pressure level of IO points at 100Hz, 200Hz and 300Hz ranges from 90.7 dB~103.5 dB, 62.3 dB~94.1 dB, 41.1 dB~88.6 dB. It can be seen that the noise at 100Hz is significantly higher than that at 200Hz, and the noise sound pressure level at 300Hz is lower than that at 200Hz.

In order to evaluate the noise reduction effect of the whole car room with the secondary sound source, the average sound pressure level of the whole car room before and after the laying of the 3 secondary sound source position schemes are calculated according to the formula (3), the results are shown in Table 6.

Table 6. Noise reduction in vehicle indoor after adds secondary sound source

Place scheme	Frequency/(Hz)	SPL_3/(dB)	SPL_4/(dB)	ΔE/(dB)
scheme 1	100	105.5	99.6	5.9
	200	85.1	79.6	5.5
	300	72.7	70.1	2.6
scheme 2	100	105.5	95.1	10.4
	200	85.1	76.0	9.1
	300	72.7	64.3	8.4
scheme 3	100	105.5	100.6	4.9
	200	85.1	82.2	2.9
	300	72.7	71.8	0.9

As can be seen from Table 6, while scheme 2 has the greatest noise reduction which is 8.4dB-10.4 dB, scheme 1 is the second and noise reduction is 2.6 dB-5.9 dB, scheme 3 has the lowest noise reduction which is 0.9 dB-4.9dB.

From the above results, it can be seen that scheme 1 is the optimal case to achieve the effective control of noise. Moreover, the effect of frequency on noise reduction when selecting this optimal scheme is discussed later.

3.3 Effect of Sound Source Frequency on Noise Reduction

Further analysis of the effect of frequency on noise reduction when the secondary sound source is placed in the same height and symmetrical position as the crew head on the side wall of the car. According to the frequency range of the indoor noise source, the primary and secondary sound source frequencies are from50 Hz to 800 Hz, the frequency resolution is 50 Hz, the amplitude is determined according to the sound pressure level of each frequency of the vehicle, and the phase can be calculated according to the distance between the primary sound source and the secondary sound source. The calculation of the noise reduction at each frequency is shown in Fig. 15.

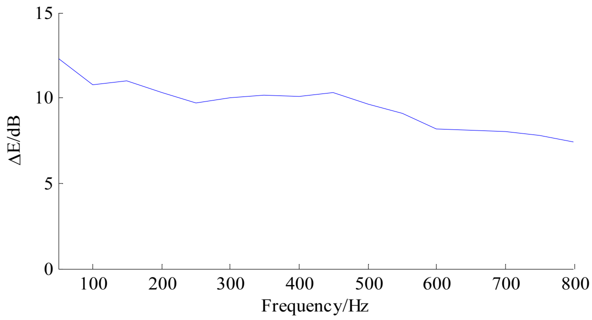

Fig. 15. Noise reduction at each frequency after sidewall adds secondary sound source

As can be seen from Fig. 15, noise is reduced by at least 7.4 dB within 50 Hz-800 Hz, and the noise reduction effect is decreased with the increasing frequency. That is because when the noise frequency is higher, the sound wave changes rapidly. The match between the secondary sound source and the primary sound source is more difficult; therefore, the noise reduction ability decreases gradually as the frequency increases. It is shown that the scheme can achieve a greater noise reduction at various frequencies. Therefore, in practice, we can consider placing secondary sound sources on the side wall of the car with the head of the crew and the symmetrical position.

4 Conclusions

In this paper, the secondary sound sources in the active noise control system are placed at different positions in the interior space of the vehicle, and the sound pressure level and distribution of the output response in the vehicle interior are calculated by using the finite element model, the noise reduction effect of the vehicle is evaluated, and the conclusions are as follows:

(1) The local noise reduction effect of the secondary sound source placed on the side wall of the

driver's head, the top cover position above the head, and the chassis below the seat is evaluated. It is shown that the noise reduction in the vicinity of the driver's head is larger, both above 10.8 dB;

(2) In order to evaluate the effect of noise reduction in the whole space in the automobile room, the distribution scheme of 4 secondary sound sources was studied. It is shown that the noise reduction effect is best when the inner wall of the car and the head of the crew at the same height are placed with the secondary sound source.

(3) Under the optimal scheme, the noise reduction effect at multiple frequencies is studied within the engine noise frequency range. It is shown that the noise reduction is above 7.4 dB in the range of 50 Hz to 800 Hz.

Therefore, in order to solve the problem that the secondary sound source is difficult to be positioned because of the body structure and interior decoration of the car, this paper presents an interior secondary sound source placement method which can effectively reduce the interior noise of the car. This method has important practical application significance.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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