Source Path Contribution Analysis for Vehicle Indoor Pass-By Noise

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Compared with traditional frequency domain source path contribution (F-SPC), time domain source path contribution (T-SPC) can effectively implement contribution analysis for unsteady sound sources. Since the results obtained by this method are time domain data, which can be replayed for listening tests and further sound quality analyses, the characteristics of noises and their contributions can be understood and mastered more intuitively and comprehensively. Considering this, source contribution analysis of vehicle indoor pass-by noise is conducted utilizing time domain source path contribution. The accuracy of this procedure is verified by adding an additional sound source which is easy to implement. The results show that engine and tires contribute 52% and 40% respectively, but exhaust outlet and intake inlet contribute only 5% and 3% separately. The T-SPC results are of significance for further development of effective automotive noise control programs.

To reduce the pass-by noise from vehicles, ease the problem of noise pollution, a series of regulations have been proposed.[1] However, the pass-by noise test methods mentioned in these regulations, which can only be carried out on outdoor proving ground, are vulnerable to environmental factors and poor reproducibility. To overcome these shortcomings, an indoor simulation test method for pass-by noise in a semi-anechoic chamber is proposed,[2] and corresponding laws and regulations are also in development. Compared with an outdoor test on a proving ground, the indoor pass-by noise test is of good repeatability under a controlled environment, which can significantly improve the efficiency. Given this, a combination method of source path contribution (SPC, also known as transfer path analysis or TPA) and indoor pass-by noise test to identify the main sources is presented.[3-7] In this article the measurements were performed using SPC solutions from Brüel & Kjær, both hardware as well as software.

The SPC method can separate and sort out the main sound source contributions of a complex system and is widely used in the field of vehicle noise control. Fleszar[4] and Genuit[5] combined the airborne source quantification technique with the SPC method to obtain the strength of sound sources by a matrix inversion method at first, and then used the SPC method to acquire the gross noise value and the contribution of each source. Janssens[8] proposed a high efficiency SPC method based on the parametric model, which can obtain the working loads by estimating model parameters under different working conditions. The data processing of the above methods is performed in the frequency domain, namely, frequency domain source path contribution (F-SPC). F-SPC is usable for steady or quasi-steady sources but not for unsteady sources. Vehicle acceleration pass-by noise is obviously unsteady. To surmount this deficiency, a time domain source path contribution (T-SPC) method is presented. The outputs of T-SPC are time domain signals, which can be replayed for listening tests and further sound quality analyses.

The accuracy verification of T-SPC has been presented in several documents. For example, Bogema[9] and Schumacher[10] used a controllable sound source and an engine vibration noise simulator on a simplified vehicle model to analyze the contribution of each source to the interior noise by T-SPC and F-SPC respectively. The comparison results show that the T-SPC method is in good agreement with the results of the F-SPC method. To the best of our knowledge, references including accuracy verification of T-SPC for indoor pass-by noise contribution analysis have not been found to date. This article presents source path contribution analysis of indoor pass-by noise based on the time domain source path contribution.

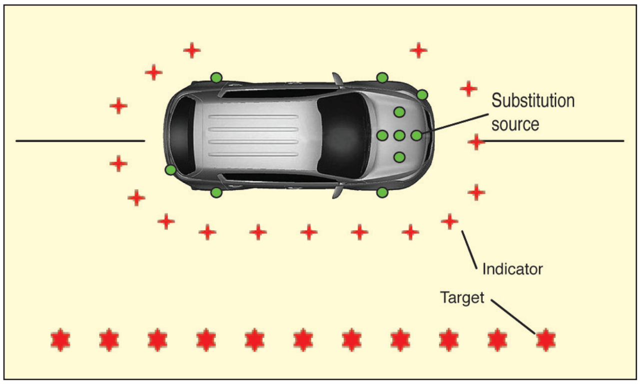

Figure 1. Substitution source model.

Theory of Time Domain Source Path Contribution

Contribution analysis for sound sources of pass-by noise is based on a substitution source model, which means that the actual sources will be assumed as several substitution (point) sources.[11,12] Then, the strength of each substitution source will be determined by the frequency response function (FRF, sometimes also called transfer function) of substitution sources to indicators combined with the sound pressure signals obtained by indicators. Lastly, FRFs of substitution sources to targets and the strength of the substitution sources will be used to determine the contributions of actual sources to the targets. The substitution source model is shown in Figure 1.

Assuming that the system is linear and time-invariant, the sound pressure received by each target is equal to the vector sum of sound pressures transmitted through different paths.[13,14] Therefore, the sound pressure signal at each target can be expressed as:

$$p_i(t) = \sum_{j=1}^{n} p_{ij}(t) \tag{1}$$

where t is a time variable; $p_i(t)$ is the sound pressure signal received by the ith target; $p_{ij}(t)$ is the sound pressure contribution of the jth substitution source to the ith target; and m, n in i=1,2, . . . ,m, j=1,2, . . . ,n, is the respective number of targets and substitution sources.

The contribution of each source path to the target can be expressed as a convolution of excitation and unit impulse signal, so Eq. 1 can be expressed as:

$$p_i(t)=\sum_{j=1}^{n}\int_{-\infty}^{+\infty} h_{ij}(t-\tau)q_j(\tau)d\tau \tag{2}$$

where τ is a time variable; $q_j(t)$ is the volume velocity signal of the jth substitution source; and $h_{ij}(t)$ is the unit impulse response function of the ith target to the jth substitution source.

It is known from Eq. 2 that the strength of each substitution source in working conditions and the unit impulse response functions of each target to substitution sources are a prerequisite to get sound pressure signals of pass-by noise at targets. Besides, because the ideal impulse excitation cannot be applied to the system, the unit impulse response functions of the system cannot be obtained in the time domain directly. Hence, FRFs are always obtained in the frequency domain at first, and then converted into the time domain by inverse Fourier transform. Because the input and output signals are all known in the substitution source method, FRFs of the whole system can be obtained by an H_1 estimate:

$$\boldsymbol{H}^I(\omega)=\begin{bmatrix} H_{11}^I(\omega) & H_{12}^I(\omega) & \cdots & H_{1n}^I(\omega) \\ H_{21}^I(\omega) & H_{22}^I(\omega) & \cdots & H_{2n}^I(\omega) \\ \vdots & \vdots & \ddots & \vdots \\ H_{r1}^I(\omega) & H_{r2}^I(\omega) & \cdots & H_{rn}^I(\omega) \end{bmatrix} \quad (3)$$

$$\boldsymbol{H}^R(\omega)=\begin{bmatrix} H_{11}^R(\omega) & H_{12}^R(\omega) & \cdots & H_{1n}^R(\omega) \\ H_{21}^R(\omega) & H_{22}^R(\omega) & \cdots & H_{2n}^R(\omega) \\ \vdots & \vdots & \ddots & \vdots \\ H_{m1}^R(\omega) & H_{m2}^R(\omega) & \cdots & H_{mn}^R(\omega) \end{bmatrix} \quad (4)$$

where $\boldsymbol{H}^I(\omega)$ represents the FRF matrix of indicators to substitution sources; $\boldsymbol{H}^R(\omega)$ represents the FRF matrix of targets to substitution sources; $H_{lj}^1(\omega)$ represents the FRF of the ith indicator to the jth substitution source, in which l=1,2, . . . ,r, and r is the number of indicators and not less than n; $H_{ij}^R(\omega)$ represents the FRF of the ith target to the jth substitution source.

Based on the obtained FRFs, the time domain deconvolution method is used to determine the strength of sound sources. At the start of this process, the corresponding indicators are arranged around the parts of interest, and the sound pressure signals measured by indicators can be described as:

$$\boldsymbol{p}^I(t)=\int_{-\infty}^{+\infty}\boldsymbol{h}^I(t-\tau)\boldsymbol{q}^S(\tau)d\tau \quad (5)$$

where $\boldsymbol{p}^I(t)$ is the column vector of measured sound pressure signals at r indicators; $\boldsymbol{q}^S(\tau)$ is the column vector of measured volume velocity signals at n substitution sources, and $\boldsymbol{h}^I(t-\tau)$ is the $r \times n$ matrix constituted by unit impulse response functions of indicators to substitution sources.

To obtain the strength of sources by Eq. 5, deconvolution should be conducted at first. Supposing that the unit impulse response function matrix of the deconvolution filter is a $n \times r$ matrix $\boldsymbol{h}^D$, then it can be written as:

$$\boldsymbol{q}^S(t)=\int_{-\infty}^{+\infty}\boldsymbol{h}^D(\tau')\boldsymbol{p}^I(t-\tau')d\tau' \quad (6)$$

where: τ' is a time variable.
Put the expression of sound pressure signal in Eq. 5 into Eq. 6:

$$\boldsymbol{q}^S(t)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\boldsymbol{h}^D(\tau')\boldsymbol{h}^I(t-\tau'-\tau)d\tau'\boldsymbol{q}^S(\tau)d\tau \quad (7)$$

To establish Eq. 7 as valid, the following condition should be satisfied:

$$\int_{-\infty}^{+\infty}\boldsymbol{h}^D(\tau')\boldsymbol{h}^I(t-\tau'-\tau)d\tau' = diag\left[\delta_1(t-\tau),\delta_2(t-\tau),\cdots,\delta_n(t-\tau)\right] \quad (8)$$

where δ_1, δ_2, . . . , δ_n are Dirac functions.
The Fourier transform is performed on Eq. 8 as follows:

$$\boldsymbol{H}^D(\omega)\boldsymbol{H}^I(\omega)=\boldsymbol{E} \quad (9)$$

where $\boldsymbol{H}^D(\omega)$ and $\boldsymbol{H}^I(\omega)$ stand for the Fourier transform of $\boldsymbol{h}^D(t)$ and $\boldsymbol{h}^I(t)$ respectively, and $\boldsymbol{E}$ stands for a unit matrix.

According to Eq. 9, $\boldsymbol{H}^D(\omega)$ is a generalized inverse of $\boldsymbol{H}^I(\omega)$, which can be directly obtained by Eq. 3. However, due to the impact of noise in the process of the substitution source method test, there will be several small singular values caused by noise in the FRF matrix, which will be further amplified during inversion and affect the accuracy of the obtained source strength. To solve this problem, the truncated singular-value decomposition (TSVD) is used for the matrix $\boldsymbol{H}^I(\omega)$ to reduce the impact of noise and improve the accuracy of results before $\boldsymbol{H}^D(\omega)$ is obtained by inverse operation.[15-18]

Considering all the points in a frequency band, the FRF matrix of the deconvolution filter is a series of complex sequences, $H(k)$ essentially, and k represents the sequence number of FRF complex sequences. When using the frequency sampling method to build a filter, the unit impulse response $h(d)$ should be obtained by inverse discrete Fourier transform of $H(k)$ first, shown as Eq. 10, then z transformation is applied to the unit impulse response by setting $z = e^{j\omega}$, and the FRFs of the finite-impulse response (FIR) filter can be obtained further as shown in Eq. 11:

$$h(d)=\frac{1}{N}\sum_{k=0}^{N-1}H(k)e^{j2\pi kd/N} \quad (10)$$

$$H(e^{j\omega})=\frac{e^{-j\omega(N-1)/2}}{N}\sum_{k=0}^{N-1}\frac{H(k)e^{-j\omega/N}\sin\left(\frac{\omega N}{2}\right)}{\sin\left(\frac{\pi}{2}-\frac{\pi k}{N}\right)} \quad (11)$$

where d is the sequence number of unit impulse responses, N is the sequence length of FRFs, ω is the digital frequency, and j is the imaginary unit.

After the filter was built, the strength of sources in working conditions can be expressed as:

$$\begin{bmatrix} q_1^S(t) \\ q_2^S(t) \\ \vdots \\ q_n^S(t) \end{bmatrix}=\begin{bmatrix} h_{11}^D(t) & h_{12}^D(t) & \cdots & h_{1r}^D(t) \\ h_{21}^D(t) & h_{22}^D(t) & \cdots & h_{2r}^D(t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{n1}^D(t) & h_{n2}^D(t) & \cdots & h_{nr}^D(t) \end{bmatrix} * \begin{bmatrix} p_1^I(t) \\ p_2^I(t) \\ \vdots \\ p_r^I(t) \end{bmatrix} \quad (12)$$

where '*'denotes the convolution operation, $q_j^S(t)$ indicates the time domain signal of the strength of the jth substitution source, $p_l^I(t)$ indicates the sound pressure signal of the lth indicator, and $h_{il}^D(t)$ represents the unit impulse response function of the Ith indicator to the jth substitution source.

Ultimately, the FRF matrix of targets to substitution sources is constructed as a time-domain filter $\boldsymbol{h}^F$, so the sum of the contribution of each substitution source to targets can be expressed as:

$$\begin{bmatrix} p_1^R(t) \\ p_2^R(t) \\ \vdots \\ p_m^R(t) \end{bmatrix}=\begin{bmatrix} h_{11}^F(t) & h_{12}^F(t) & \cdots & h_{1n}^F(t) \\ h_{21}^F(t) & h_{22}^F(t) & \cdots & h_{2n}^F(t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{m1}^F(t) & h_{m2}^F(t) & \cdots & h_{mn}^F(t) \end{bmatrix} * \begin{bmatrix} q_1^S(t) \\ q_2^S(t) \\ \vdots \\ q_n^S(t) \end{bmatrix} \quad (13)$$

where $p_i^R(t)$ is the sound pressure signal of the ith target, and $h_{ij}^F(t)$ is the unit impulse response function of the ith target to the jth substitution source.

Test and Contribution Analysis of Indoor Pass-By Noise

The test and contribution analyses of pass-by noise on a five-passenger vehicle were carried out under acceleration in third gear. It is known from the results of a previous tests that the pass-by noise of the right side of the vehicle was larger than that of the left side, so only the right side of the vehicle was used for testing and contribution analysis. This test was performed in a semi-anechoic chamber with a chassis dynamometer. According to the noise radiation pattern of the vehicle, 11 substitution sources were used to substitute the parts of interest. The arrangement of these substitution sources is shown in Table 1. During the test process, 16 indicators were arranged around sound sources at a

Table 1. Distribution information of assumed sound sources.

Parts	Name of Source	Position of Source
Tires	LF tire	Near left front tire
	RF tire	Near right front tire
	LR tire	Near left rear tire
	RR tire	Near right rear tire
Exhaust outlet	Right exhaust	Near outlet of tail pipe
Intake inlet	Left intake	Near inlet of intake pipe
Engine	Engine bottom center	Bottom of engine and near bottom of oil pan
	Engine front center	Front center of engine and near intake manifold
	Engine rear center	Rear center of engine and near exhaust manifold
	Engine left	Left side of engine and near gearbox
	Engine right	Right side of engine

Figure 2. Site layout of indoor pass-by noise test.

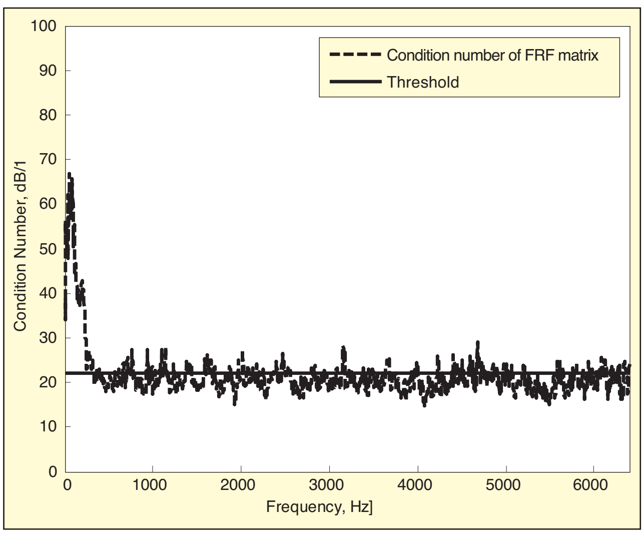

Figure 3. Condition number of FRF matrix.

height of 0.5 m, and a linear microphone array of 11 targets was used to measure sound pressures with a uniform spacing of 2 m. The array was placed on the right side of the vehicle at 7.5 m from the centerline of the vehicle and at a height of 1.2 m. The test site layout is shown in Figure 2.

The test was conducted in two steps:

1. Measure the FRFs under static conditions. To get the FRF matrix of indicators to substitution sources and that of targets to substitution sources, the B&K Type 4295 volume-velocity source was used. During the test, the volume-velocity signals were recorded with a B&K Type 4299 volume-velocity adaptor, and at the same time, the sound pressures at indicators and targets were recorded by B&K Type 4189 free-field microphones. Then, FRF matrices were obtained by H_1 estimates.
2. Measure the sound pressures under working conditions. During the test, the third gear was selected and the vehicle accelerated to full throttle. The sound pressures of indicators and targets were also recorded at the same time.

Once FRF matrices and the operational data are obtained, the strength of substitution sources should be determined first, and the matrix inversion method is always used in this process. However, the interfering noise will have a great impact on small singular values of the FRF matrix, which will lead to large differences between the measured and computed results. Therefore, the TSVD method for the FRF matrix is always used before the inversion of the matrix. According to the condition number of the FRF matrix of indicators to substitution sources shown in Figure 3, a threshold of 22 dB is chosen.

It is worth noting that the effective lower limit frequency of the B&K Type 4295 Omni-Source is 50 Hz, and the main frequency range of the sound sources of interest is below 6000 Hz under third gear acceleration. This means that the frequency bands of the FRF, matrix which are below 50 Hz or above 6000 Hz, will be filtered out before the FIR filter is constructed. Figure 4 shows the comparison between the FRF of the deconvolution filter and the inverse FRF in the FRF matrix, which represents the relationship between indicators and sound sources, where the broken line denotes the inverse FRF and the solid line denotes the FRF of the deconvolution filter. It can be seen that, in the frequency band from 50 Hz to 6000 Hz, the two curves almost coincide.

After the FRF matrix of the deconvolution filter is obtained,

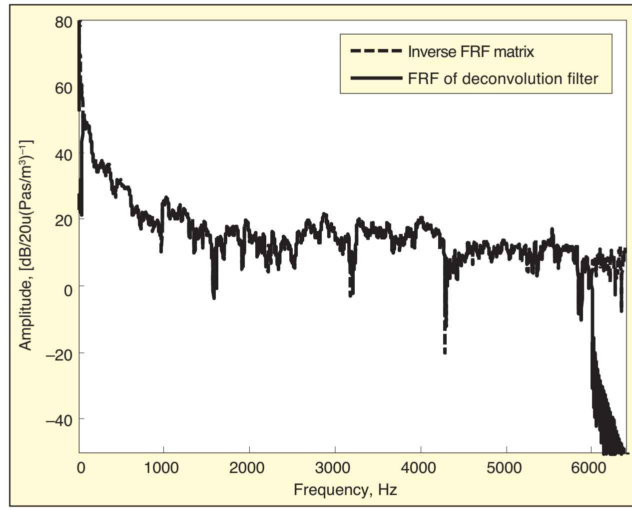

Figure 4. Comparison of FRF of deconvolution filter and inverse FRF.

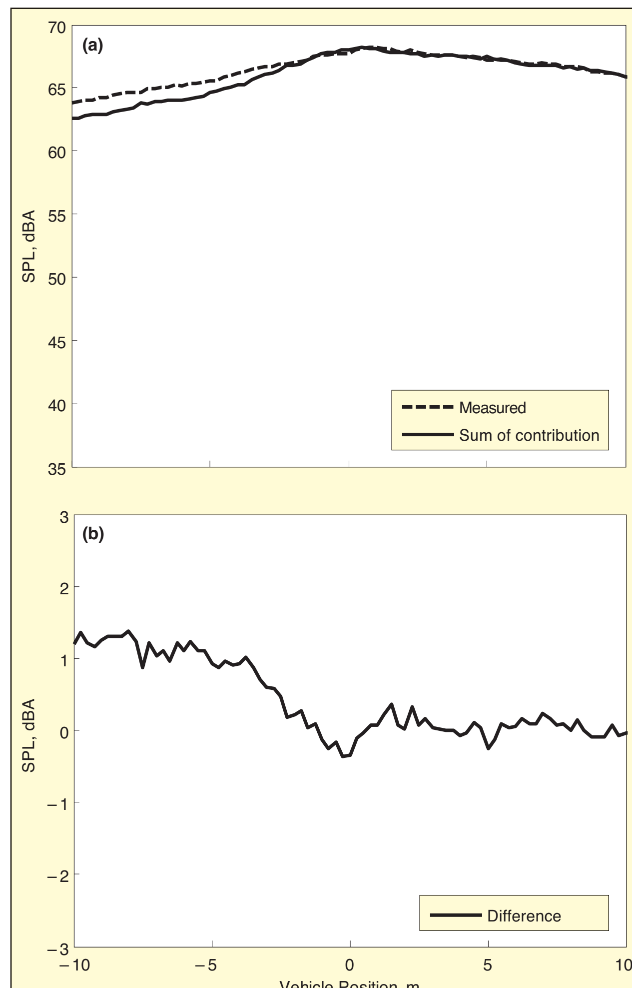

Figure 5. Indoor pass-by noise: a) Comparison between measurement value and synthetic value; b) Difference.

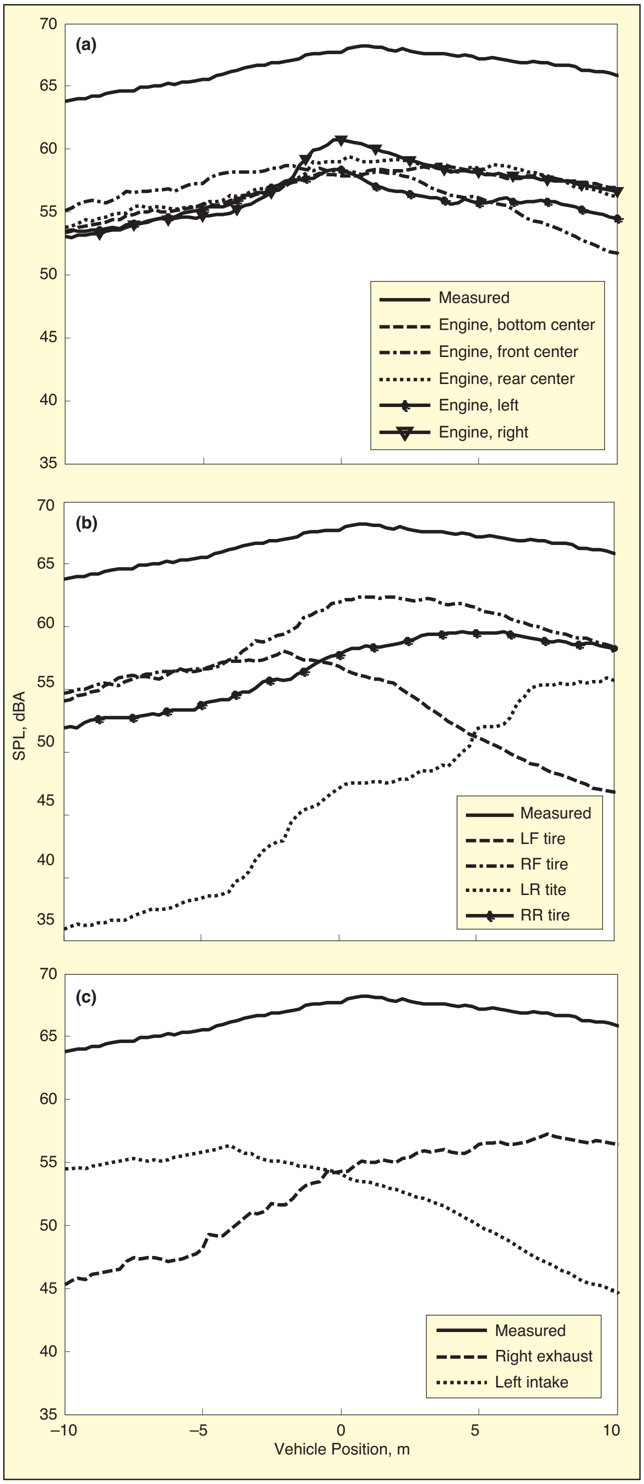

Fig. 6. Contribution of each source: (a) Engine, (b) Tires, (c) Exhaust outlet and intake inlet.

time-domain signals of the sound pressure measured by indicator microphones in working conditions can be substituted into Eq. 12 to get the strength of substitution sources. Then the contribution of each substitution source to targets can be obtained by Eq. 13, and finally, on the basis of vehicle speed information, the contribution of each target at a specific time is truncated and spliced to acquire the result of contribution analysis for indoor pass-by noise according to the rule of indoor pass-by noise synthesis.

Figure 5a shows a comparison of the pass-by noise curve obtained by summing the contributions with the measured indoor test, where the former is indicated by a solid line and the latter by a broken line. Figure 5b shows the difference between the two values, and in the entire test area, the difference between the two values is small – a maximum value of 1.5 dB(A). Therefore, the value of pass-by noise synthesized by summing contributions of noise sources can be considered valid.

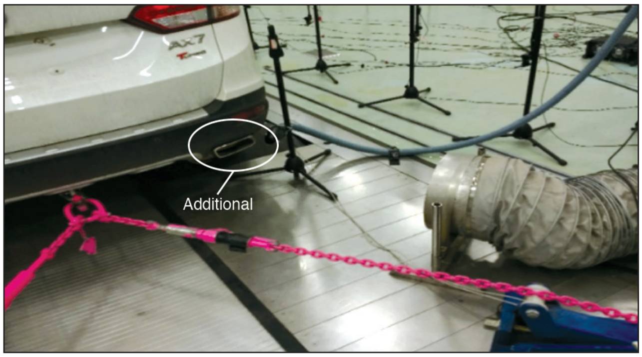

Figure 7. Location of an additional source.

Figure 6 shows the results obtained by indoor pass-by noise contribution analysis: a) demonstrates the contributions of the engine; b) demonstrates the contributions of the tires; and c) demonstrates the contributions of the exhaust outlet and intake inlet. As shown in the figures, the contributions of engine noise are great throughout the entire test area. With respect to the contributions of tires, since the test microphone array is located on the right side of vehicle, the contributions of right tires always dominate in the test area. Furthermore, the contribution of the right front tire is larger than that of rear one, because the vehicle has front-wheel drive.

For the left tires, due to obstruction of the body in noise transmission, the left front tire has a large contribution to targets before the vehicle passes the test centerline, and the contribution becomes smaller after the vehicle has passed the test centerline. In contrast, the left rear tire has an opposite case. For the intake inlet and exhaust outlet, the contribution of the former is greater than that of the latter before the vehicle passes the test centerline, and an opposite case occurs after the vehicle has passed the test centerline.

To further clarify the impact of each sound source to the pass-by noise of the vehicle, this article analyzes the contribution of each source at the vehicle position where the maximum value is located. From Figure 5a we can see that the maximum is located at 0.75 m, with a value of 68.2 dB(A), and the sorted results are shown in Table 2. The table shows that the engine, which accounts for 52%, plays a major role in pass-by noise, followed by the contributions of tires accounting for 40%, and the exhaust outlet and intake inlet account for rather smaller contributions at 5% and 3%, respectively.

Results Verification by Adding Sound Sources

To verify the accuracy of T-SPC-based pass-by noise contribution analysis, we propose an easy verification method by adding an additional sound source. The additional sound source with different energy is installed near one substitution source. Here we chose the exhaust outlet, and the detailed position is shown in Figure 7. During the test, the excitation voltages of the additional sound source were set to 0.5 and 1 volt, respectively, and the corresponding contributions are analyzed.

Figure 8a and 8b show the contributions of the intake inlet and exhaust outlet before and after the additional sound source was added, respectively, where the solid lines indicate the contribution analysis results without the additional source, the dash-dot lines indicate the results with the additional source driven by an excitation voltage of 0.5 V, and the dashed lines indicate the results with the additional source driven by an excitation voltage of 1 V. As shown in the figures, the additional source has an ignorable impact to the contribution of the intake inlet but a prominent

Table 2. Contribution analysis for each component.

Name	Contribution, dB(A)	Ratio, Percent
Engine	65.7	52.3
Tires	64.6	40.0
Exhaust outlet	55.2	4.6
Intake inlet	53.5	3.2

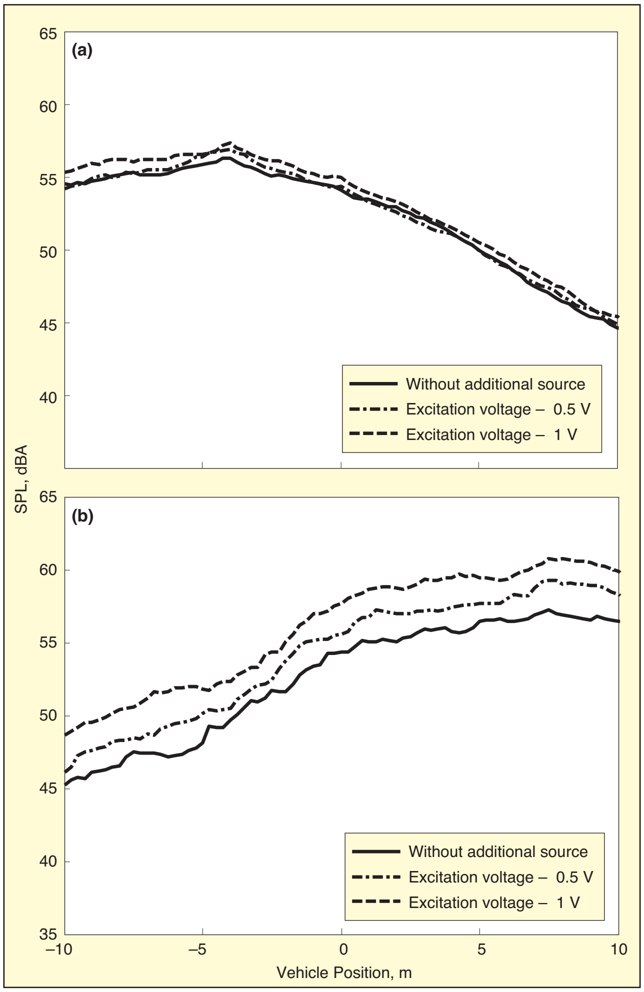

Figure 8. Comparison of contributions before and after adding the additional source; a) Intake inlet; b) Exhaust outlet.

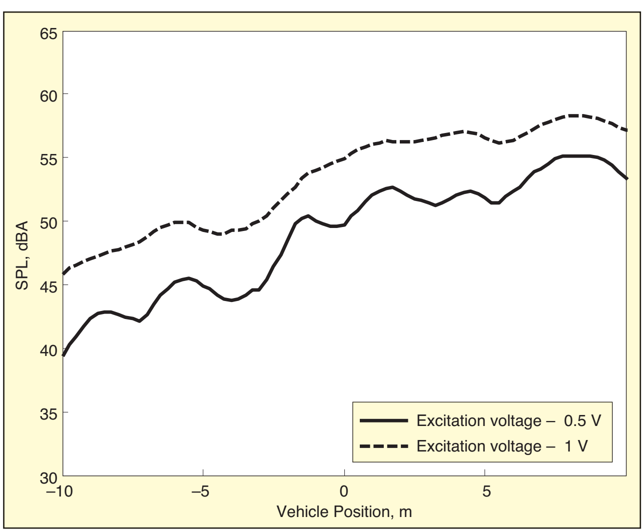

Figure 9. Comparison of contribution results of additional source to targets.

impact to the contribution of the exhaust outlet, which increases with the excitation voltage.

Figure 9 shows contribution of the additional source to targets, where the solid line represents the result of 0.5 V and the broken line represents the result of 1 V. The approach to acquire contributions of the additional source shown in both lines uses the contribution from the exhaust outlet to targets with the additional source minus the contribution without the additional source. The theoretical differences between the two lines should be 6 dB(A), but the actual results are shown in the Figure 9, where differences between the two lines approximate 6 dB(A), and only a small number of ignorable differences exist. Given this, we concluded that the indoor pass-by noise contribution analysis based on T-SPC is accurate and the separation results are reliable.

Conclusions

A vehicle SPC model of indoor pass-by noise was established and the source contribution analysis in the time domain was conducted. The results show that the maximum value of pass-by noise of this vehicle was 68.2 dB(A). The contribution of the engine accounts for 52% followed by the contribution of tire noise which accounts for 40%. The contribution of intake inlet and exhaust outlet only accounted for 3% and 5%, respectively. Therefore, the T-SPC-based contribution analysis method can effectively separate the main sound sources from pass-by noise. In addition, the verification test by adding an additional source shows that the method is accurate and reliable.

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