The Transfer Paths' Contribution Analysis to Floor Vibration of Metro Vehicle

peng laixian

Southwest Jiaotong University <https://orcid.org/0000-0001-5380-5310>

Jiaxing Nie

Southwest Jiaotong University

Jian Han (✉ super_han@126.com)

School of Mechanical Engineering, Southwest Jiaotong University, Chengdu, China

Caiying Mi

Southwest Jiaotong University

Original Article

Keywords: OTPA, Secondary Suspension, Contribution Analysis, Transfer Path Optimization Scheme, Metro Trains

Posted Date: October 12th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-88804/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

The Transfer paths' Contribution Analysis to Floor Vibration of Metro Vehicle

Laixian Peng¹, Jiaxing Nie², Jian Han^{*1}, Caiying Mi¹

1 School of Mechanical Engineering, Southwest Jiaotong University, Chengdu, China, 610031

2 State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu, China, 610031

*E-mail: hanjian@swjtu.edu.cn

Abstract

Noise control is one of key issues to improve the ride comfort of metro trains. To find out the excitation source and its transfer path is an important prerequisite for noise control. The sound source identification results found that the significant noise source in metro trains is the structural-borne sound radiated by floor vibration. Based on the OTPA method, this study presents a method considering the amplitude and phase of the excitation to analyze the contribution of the secondary suspension path to the floor vibration. The results show that the energy of the passenger room noise mainly concentrates on the frequency range of 300~800Hz, caused by floor vibration; in the frequency range of 300~800Hz, the vertical direction of the anti-rolling torsion bar area provides the maximum contribution to the floor vibration, followed by the longitudinal direction of the air spring area. On the basis of contribution analysis, a transfer path optimization scheme is proposed, which may provide reference for future metro trains noise control.

Keywords

OTPA, Secondary Suspension, Contribution Analysis, Transfer Path Optimization Scheme, Metro Trains

Introduction

In recent years, China's metro trains have become an indispensable part of urban public transportation. With the rapid development of the metro car, new challenges have emerged, necessitating further research. Noise control is one of key issues to improve the ride comfort of metro trains. To find out the excitation source and its transfer path is an important prerequisite for noise control.

When the train is running at a speed of 30-80km/h, wheel-rail rolling contact becomes the main source of excitation^[1,2]. Fan et al.^[3] found that the major source of the interior noise is the structural-borne sound radiated by floor vibration. Zhang et al.^[4] found that the bogie area noise and the sound source at the middle of the coach contribute significantly to the interior noise. The most direct and effective method of noise control is to eliminate the excitation source. Furthermore, it is also important to identify the transfer path of the main source of excitation.

The transfer path analysis (TPA) method^[5-8] is an effective method to obtain the contribution of each transfer path. However, it takes a lot of manpower and time to get all the transfer functions. Operational transfer path analysis (OTPA) is an advanced vibration and noise transfer path identification and contribution evaluation method^[9]. Klerk et al.^[10] elaborated on the theory, the modeling principles and the precautions of the OTPA method and applied the

OTPA method to practical engineering. De Sitter^[11] applied OTPA to study the NVH problems of the car, and the results showed that no disassembling was required and operational forces also don't have to be eliminated. Keizer et al.^[12] used the OTPA method to analyze the contribution of the noise sources of a ship, such as engines, gearboxes, and propellers. Robert^[13] applied OTPA to study the vibration and noise problems of a high-speed train bogie, and it was found that OTPA was a faster and often cheaper way than traditional TPA. However, when OTPA is applied in complex mechanical systems, there is a problem of crosstalk between vibration sources^[14]. So, Putner^[15] pointed out that the reference points of the excitation source should be as close as possible to the excitation source to reduce the effect of crosstalk. Mihkel^[16] applied singular value decomposition (SVD) and principal component analysis (PCA) to solve the crosstalk problem of OTPA, which cancelled crosstalk by cutting off small singular values or principal components. Cheng et al.^[17] proposed a novel crosstalk cancellation method based on independent component analysis (ICA) to eliminate crosstalk effects between reference signals of operational transfer path analysis (OTPA). Zhang^[18] performed cross-talk cancellation pre-processing on experimental data to achieve more accurate data for the transfer path analysis, and the experiment proved that it can obtain more accurate

contribution results for each path. Lei ^[19] used the OTPA method to analyze the transfer paths of the metro vehicle interior noise and found that the major path in the structure-borne paths is the vertical damper on both side of the bogie.

In summary, the OTPA method has been gradually applied in the field of railway transportation to analyze the contribution of transfer paths. However, the contribution in the vertical, lateral and the longitudinal direction of the secondary suspension components are less differentiated in previous studies. The transfer character of the secondary suspension components in the three directions are quite different. The target response is the superposition result of each path vector, but the phase of each path was not analyzed in detail in the field of rail transit vehicles in the above studies. Based on the result of sound source identification, this study finds that the significant noise source in metro trains is the structural-borne sound radiated by floor vibration. Therefore, based on the OTPA method, a method considering the amplitude and phase of the excitation is presented to analyze the contribution of the secondary suspension path to the floor vibration. At the same time, an optimization scheme is proposed to ensure the effectiveness of the transfer paths optimization.

OTPA method theory

OTPA is a signal processing method, which uses numerical calculation means to obtain the transfer functions between the input and output signals, to obtain the contribution of the excitation sources or transfer paths to the target point response ^[20-23].

The OTPA method theory is based on the system that is linearized and time-invariant. The input and output of the system can be expressed as:

$$\mathbf{Y}(j\omega) = \mathbf{X}(j\omega)\mathbf{H}(j\omega) \quad (1)$$

Where $\mathbf{Y}(j\omega)$ is the output vector of the response points and $\mathbf{X}(j\omega)$ is the input vector of the reference points, $\mathbf{H}(j\omega)$ is the transfer functions matrix.

For the general vibration and noise measurements, the collected signals are usually vibration acceleration signals and sound pressure signals. According to the formula $\mathbf{H}(j\omega) = \mathbf{X}(j\omega)^{-1}\mathbf{Y}(j\omega)$, the transfer functions matrix can be obtained as follows.

$$\begin{pmatrix} H_{a1} \\ \mathbf{M} \\ H_{an} \\ H_{s1} \\ \mathbf{M} \\ H_{sm} \end{pmatrix} = \begin{pmatrix} a_{11} & L & a_{1n} & s_{11} & L & s_{1m} \\ a_{21} & L & a_{2n} & s_{21} & L & s_{2m} \\ a_{31} & L & a_{3n} & s_{31} & L & s_{3m} \\ a_{41} & L & a_{4n} & s_{41} & L & s_{4m} \\ \mathbf{M} & \mathbf{O} & \mathbf{M} & \mathbf{M} & \mathbf{O} & \mathbf{M} \\ a_{k1} & L & a_{kn} & s_{k1} & L & s_{km} \end{pmatrix}^{-1} \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \\ \mathbf{M} \\ Y_k \end{pmatrix} \quad (2)$$

Where k is the number of operating conditions, n , m respectively represents the number of vibration reference points and acoustic reference points, and there is a necessary condition is $k > m + n$. However, the equation is solved directly, numerical problems will appear and the wrong transfer functions matrix may be obtained. Therefore, there is needed to solve the problem of solving the equation by singular value decomposition (SVD).

The reference points matrix $\mathbf{X}$ can be expressed as:

$$\mathbf{X} = \mathbf{U}\mathbf{S}\mathbf{V}^T \quad (3)$$

Where $\mathbf{U}$ is a $k \times k$ matrix, $\mathbf{U}\mathbf{U}^T = \mathbf{I}$, $\mathbf{V}$ represents a $(m+n) \times (m+n)$ matrix, $\mathbf{V}\mathbf{V}^T = \mathbf{I}$. $\mathbf{S}$ is a $k \times (m+n)$

matrix and $\mathbf{S} = \begin{bmatrix} \mathbf{Z} & 0 \\ 0 & 0 \end{bmatrix}$, here $\mathbf{Z} = \text{diag}(\sigma_1 \cdots \sigma_r)$. At this moment, the matrix has been decoupled by SVD and a part of the noise interference is removed by the principal component analysis (PCA) method. Thereby the accuracy of the transfer functions matrix is improved. However, eigenvalue decomposition only applies to square matrices, so mathematical transformation are required when performing SVD:

$$\mathbf{X}^T\mathbf{X} = \mathbf{V}\mathbf{S}^T\mathbf{U}^T\mathbf{U}\mathbf{S}\mathbf{V}^T = \mathbf{V}(\mathbf{S}^T\mathbf{S})\mathbf{V}^T \quad (4)$$

$$\mathbf{X}\mathbf{X}^T = \mathbf{U}\mathbf{S}\mathbf{V}^T\mathbf{V}\mathbf{S}^T\mathbf{U}^T = \mathbf{U}(\mathbf{S}\mathbf{S}^T)\mathbf{U}^T \quad (5)$$

The eigenvalues of matrix $\mathbf{X}\mathbf{X}^T$ and $\mathbf{X}^T\mathbf{X}$ are equal to the square of the singular value matrix $\mathbf{X}$. The column vector of the matrix $\mathbf{V}$ is the eigenvector of the matrix $\mathbf{X}^T\mathbf{X}$, and the row vector of the matrix $\mathbf{U}$ is the eigenvector of matrix $\mathbf{X}\mathbf{X}^T$. According to formula (1):

$$\mathbf{H} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{Y} = \mathbf{X}^+\mathbf{Y} \quad (6)$$

Where $\mathbf{X}^+$ is the generalized inverse matrix of the input matrix $\mathbf{X}$.

$$\mathbf{X}^+ = \mathbf{V}\mathbf{S}^{-1}\mathbf{U}^T \quad (7)$$

The transfer functions after SVD as follows:

$$\mathbf{H} = \mathbf{V}\mathbf{S}^{-1}\mathbf{U}^T\mathbf{Y} \quad (8)$$

The target point response can be synthesized and the

contribution of the excitation sources and transfer paths can be calculated by the input signals and equation (1) after the transfer functions is obtained.

Results of interior sound source identification

A spherical microphone array with 50 channels and 12 cameras (B&K WA1565W004) is used in this sound source identification test, as shown in Figure 1. The software B&K NSI array acoustics post-processing was used for the interior noise source identification analysis, and the method is called spherical harmonics beamforming [24,25]. During the test, all the microphones on the spherical array are applied to collect the sound pressure signal. At same time the 12 cameras capture the environment. The sound source and the spatial position are corresponded precisely by the uniform spherical coordinate system, the position of the major sound sources thereby it can find. The test object is an experimental metro vehicle that has not been put into operation. The spherical array was located 1.2m from the floor above the front bogie of the TC01 (trailer, first carriage). The metro vehicle was tested at a constant speed of 60km/h and 80km/h respectively.

Figure 1. Photograph of the interior sound source identification

Figure 2 shows the interior sound source identification results of the TC01 when the metro vehicle was running on the roadbed section at speeds of 60km/h and 80km/h. The sound pressure cloud picture was calculated in a frequency range of 100~5000 Hz and the dynamic display range is 5dBA. The redder the cloud color is, the more important the sound pressure level of the sound source is.

Figure 2. The interior sound source identification results

According to Figure 2, the major noise sources in the TC01 are in the floor area when the metro vehicle was running at 60km/h and 80km/h. It indicates that excitations from the bogie area are the major sources of interior noise. On one hand, the vibration of the bogie area is directly transmitted to the floor through the structural-borne and the floor vibration radiate noise into the metro vehicle. On the other hand, the noise in the bogie area stimulates floor vibration through acoustic vibration coupling, thereby radiating the noise into the vehicle.

According to the result of sound source identification, the sound radiation of the floor area is a significant source of interior noise. To reduce interior noise, the priority is to reduce the sound radiation caused by floor vibration. Therefore, the floor vibration is chosen as the target point and the contributions of the secondary suspension to the target response are analyzed by the OTPA method. However, the floor vibration is divided into three directions, the narrow-band diagram of the three directions of the metro vehicle interior floor vibration at 60km/h are shown in Figure 3.

Figure 3. The narrow-band diagram of the floor vibration

Figure 3 shows that the vertical vibration of the floor is significantly higher than the lateral and longitudinal vibration. In addition, the vertical vibration of the floor is easier to radiate noise into the vehicle i.e. the vertical vibration is more related to the vehicle interior noise.

Therefore, the vertical vibration of the floor is chosen as the target point response to analyze the contribution of the secondary suspension paths.

The influence of phase to contribution

Because of the target point response is the result of the superposition of multiple paths vector, and the conventional transfer path contribution analysis only considers the contribution amplitude. A simplified model and uses the finite element method to analyze the contribution of the transfer paths is established in this paper. In order to find out whether the evaluation method which only considers the transfer path contribution's amplitude can effectively rank contribution to the target response of the transfer paths. The simplified model is shown in Figure 4.

Figure 4. The simplified model

The simplified model consists of a steel plate and four identical steel columns. The size of the steel plate is 1000×1000×20mm and the size of the steel column is 20×20×160mm. The four transfer paths represented by the four steel columns are evenly distributed at the four corners of the rectangular and the target point is at the geometry center of the four excitation points. The transfer functions from each excitation point to the target point can be obtained by the finite element method. Because the simplified model is a symmetric structure, the transfer function of the four paths are the same. The transfer function of a path as follows.

Figure 5. The transfer function of a path

Two different sets of excitations are added to the bottom of the four steel columns. The specific information of the excitations is shown in Table 1 and Table 2.

Table 1. Operation 1

Force	Amplitude (N)	Phase (°)	Frequency (Hz)
F ₁	50	-180	200
F ₂	40	45	200
F ₃	40	10	200
F ₄	30	-30	200

Table 2. Operation 2

Force	Amplitude (N)	Phase (°)	Frequency (Hz)
F ₁	50	45	200
F ₂	40	60	200
F ₃	40	30	200
F ₄	30	-30	200

The contribution of four excitations and the target point response can be directly obtained because the excitations and transfer functions are known, and the results are as shown in Figure 6.

(a) Operation 1

(b) Operation 2

Figure 6. The vector diagram of the transfer paths at 200Hz

Figure 6 indicates that the excitation 1 is the maximum and the excitation 4 is the minimum by sorting the contribution amplitude in the two operating conditions. In fact, in operation 2 the large amplitude of contribution does represent a large contribution to the target point because the phase difference between excitations and target point response is small. In operation 1, a large phase difference between the excitations and the target point response. Though the contribution amplitude of excitation 1 is large, it contributes to the target point in the reverse direction. Additionally, if we decrease the amplitude of excitation 1 will increase the target point response.

Hence, it is unreliable to obtain the maximum excitation by sorting the contribution amplitude when the phase difference between excitations and the target point is large. The phase of the acquired signals and the contribution vector phase are usually random in practical applications using the OTPA method. So we need a more accurate method to evaluate the results obtained by the OTPA.

Therefore, a method used to calculate the proper contribution is proposed in this paper. In the vector diagram at a certain frequency, we suppose the phase difference between the x path and the target point is θ_x , and the amplitude of x path is A_x , the contribution G_x of x path to the target point is as follows:

$$G_x = A_x \cos(\theta_x) \quad (9)$$

The path contributes positively to the target point when G_x is positive and the path gives negative contributions to the target point when G_x is negative. Since

there is a vector diagram at each frequency, the comprehensive contribution of the transfer path is calculated by summing the contribution G_x in the frequency range of 300~800Hz.

$$Z_x = \sum_{n=1}^n G_x \quad (10)$$

Where n is the number of frequencies and Z_x is the comprehensive contribution of x path to the target point.

The test of operational transfer path analysis

The basic process of the metro vehicle transfer path contribution analysis based on the OTPA method is shown in Figure 7:

Figure 7. The flow chart of transfer path analysis

Pre-test analysis shows that the excitation of the metro vehicle floor vibration can be divided into two parts: the air excitation and the structural excitation in the bogie area. The air excitation is noise in the bogie area and the structural excitation is bogie vibration caused by wheel-rail interactions. Figure 8 shows that there are 5 secondary suspension components that transmit structural excitation to the floor. The component includes the air spring, the anti-rolling torsion bar, the lateral damper, the core plate, and the traction bar. They are represented in order from □ to □ in Figure 8. In addition, The bogie area noise excitation is represented by □. During the test, the

arrangement of reference points should represent the vibration of components as much as possible. In order to prevent crosstalk, the reference points should not be too close. Because the distance between the reference point of the core plate and the traction rod is too close, and it is difficult to arrange the acceleration sensor in the traction rod area. So, core plate path (represented by ④) and traction rod path (represented by ⑤) are merged into core plate area path (represented by (4)). In summary, The reference points are arranged only at the positions of the anti-rolling torsion bar area, the lateral damper area, the core plate area, the traction bar area in the test. Considering the horizontal, vertical, and longitudinal directions of the four structural excitation paths, and the noise excitation path in the bogie area, a total of 13 transfer paths.

Figure 8. Reference points location diagram

Thus, all transfer paths are as follows:

Table 3. Transfer paths

Number of paths	Transfer paths
Path1	The vertical direction of the air spring area
Path2	The lateral direction of the air spring area
Path3	The longitudinal direction of the air spring area
Path4	The vertical direction of the anti-rolling torsion bar area
Path5	The lateral direction of the anti-rolling torsion bar area
Path6	The longitudinal direction of the anti-rolling torsion bar area
Path7	The vertical direction of the lateral damper area
Path8	The lateral direction of the lateral damper area
Path9	The longitudinal direction of the lateral damper area

Path10	The vertical direction of the core plate area
Path11	The lateral direction of the core plate area
Path12	The longitudinal direction of the core plate area
Path13	Noise at bogie area

Transfer path contribution analysis

Figure 9 shows the noise frequency spectrum of the passenger room sound from 1.6m to floor above the bogie area of TC01. The vehicle interior noise energy is mainly concentrated in the frequency range of 300~800Hz.

Figure 9. Frequency spectrum of passenger room noise above bogie

Figure 10 shows the sound pressure cloud diagram of the sound source identification test results from the passenger room of TC01 at 315Hz、 400Hz、 500Hz and 630Hz when the metro vehicle is running at 60 km/h.

Figure 10. The interior sound source identification results at 60 km/h

Figure 10 shows that the floor area is the major contributing source to the interior noise in the frequency range of 300~800Hz. Therefore, the subsequent analysis of the secondary transfer path contributions mainly focuses on the frequency range of 300~800Hz.

The transfer functions are calculated based on the

operational data of the test at the accelerated condition and the calculated value of the target point is obtained by using the reference point data of another group of typical operational data at 60 km/h. The calculated result is compared with the response of the target point obtained from the actual test, as shown in Figure 11.

Figure 11. Comparison between calculated and measured value of target point

Figure 11 shows the frequency spectrum of the target point calculated by the OTPA method and the plot of measured value versus time. The calculated value is very close to the measured value and can be well matched at each significant peak. The calculated results are accurate, so it can be used for the contribution analysis in the following part.

In order to understand the contribution level of each transfer path, the general method is to sort the overall value of the transfer path contributions and obtain the most important contribution path. Figure 12 is a histogram of the overall value of the transfer path contributions in the frequency range of 300~800Hz when the vehicle is running at a constant speed of 60 km/h.

Figure 12. The overall value of the transfer paths' contributions

Figure 12 shows that at a constant speed of 60 km/h, that the lateral direction of the lateral damper has the largest transfer path contributions overall value and the second is the vertical direction of the lateral damper. Since the target point response is the superposition of all path contribution vectors and the contributions' overall value is the superposition of the energy, only the amplitude of the transfer path contributions is considered and the influence of the phase is not considered. Therefore, the amplitude and phase of the transfer path contributions are considered in the following part, and the contributions of each path are evaluated.

Similarly, the relationship between the transfer paths and target response on amplitude and phase in the frequency range of 300-800 Hz is shown in Figure 13. Figure 13 (a) is the amplitude-frequency relationship diagram where the redder the color indicates the larger the amplitude. Figure 13 (b) is the phase-frequency relationship diagram, where the darker color (redder or bluer) indicates the bigger phase difference between the paths and the target point. The closer the color is to green, the smaller the phase difference between the paths and the target point is.

Figure 13. The amplitude-frequency and phase-frequency relationship

Figure 13 shows that the contribution amplitudes of the lateral and vertical direction of the lateral damper are larger than all other paths, but the phase of each path varies greatly at different frequencies. There is no obvious transfer path with larger amplitude and the smaller phase difference is found in this frequency band, that is, the path with a large contribution to the target response not be found. Therefore, in order to understand the transfer paths of large contributions, it is necessary to analyze the contribution of 300Hz~800Hz under the premise of considering the amplitude and phase.

Structure-borne contribution and bogie area noise excitation contribution in the frequency range of 300~800Hz are calculated by formula (15). The results show that the contribution of structural excitation is 86.6%, and the contribution of bogie area noise excitation is 13.4%. Contribution of bogie area noise excitation is small compare to the structural excitation. Therefore, in the following contribution analysis, the influence of bogie area noise excitation is ignored. In this case, contribution of structural excitation considering amplitude and phase are mainly analyzed in the following article. The contribution of the secondary transfer paths is calculated by the above method and the results are shown in Figure 14.

Figure 14. The contribution of secondary transfer paths

Figure 14 shows that only the longitudinal direction of the lateral damper makes a negative contribution in the transfer paths of the secondary system, but its influence is small in the frequency range of 300-800Hz. The vertical direction of the anti-roll torsion bar is the most significant positive contribution among the secondary transfer paths and the longitudinal direction of the air spring is the second.

To reduce the target point response, the contribution analysis method considering the overall value (Method A) and the contribution analysis method considering amplitude and phase (Method B) are going to be analyzed. It is assumed that the transfer characteristics of the secondary suspension can be arbitrarily optimized, the amplitude of the transfer path contributions is reduced to a certain extent, and the phase is unchanged. The major transfer paths obtained by the two methods are separately optimized to compare the changes in the target point response.

The lateral and vertical direction of the lateral damper are the major transfer paths obtained by Method A, and the vertical direction of the anti-rolling torsion bar and the longitudinal direction of the air spring are the major transfer paths obtained by Method B. It is assumed that the major paths obtained by Method A and Method B are optimized separately and the amplitude of the major path contribution is reduced by 20%, 40%, 60% is 80% respectively. The overall value of the target point response is obtained and compared with the initial value are shown in Table 4.

Table 4. Comparison of optimization methods

	Overall ($10^{-2} \cdot \text{m/s}^2$)		Reduce ratio	
	Method A	Method B	Method A	Method B
Initial	5.78	5.78	0.00%	0.00%
Reduce20%	5.70	5.43	1.38%	6.06%
Reduce40%	5.66	5.23	2.08%	9.52%
Reduce60%	5.69	5.19	1.56%	10.21%
Reduce80%	5.76	5.33	0.35%	7.79%

Table 4 shows that there is a significant effect on reducing the target point response to optimize the major paths obtained by method B, while the result of method A has little effect on the target point response. Therefore, it is more reasonable to use method B to evaluate the contribution of transfer paths to the target point. It can be found that the target point response is increased when the contribution of the two major paths is reduced to a certain extent. The reason is that the amplitude of the major contribution paths decreases so that the phase of the target response is close to other paths. The phase difference between some of the transfer paths and the target response is reduced, so the contribution of them is increased. The target response is increased when the contribution is increased beyond the reduced contribution amount. So, reducing the contribution of one transfer path too much is not conducive to the reduction of the target response. It can be seen from Figure 15 that the contributions of each transfer path change when the two major transfer paths obtained by method B are reduced to different degrees.

Figure 15. The change of contribution

Figure 15 shows that the contributions of other transfer paths may increase while the vertical direction of

the anti-rolling torsion bar and the longitudinal direction of the air spring decreases, such as the vertical direction of the lateral damper, the longitudinal and lateral direction of the anti-rolling torsion bar, etc. Therefore, the overall value of the target point response increases when a path decreases too much. So, we can not only blindly optimize the maximum transfer path when we want to reduce the response of the target point by optimizing transfer paths. While optimizing the maximum transfer path, we must also grasp the changes of other transfer paths to avoid excessive optimization and resulting in the target response that does not decrease.

This paper proposes a series of optimization schemes in Table 3 to maximize the optimization benefit of the transfer paths and avoid over-optimization of a certain transfer path. Assuming that once a transfer path is optimized the contribution amplitude can be reduced by 10% and the phase is remain unchanged. A variety of optimization schemes are proposed and the scheme number represents the number of optimizations, that is, scheme 12 is optimized for the transfer paths 12 times. The optimization rule is to select the maximum transfer path according to the order of contribution obtained by Method B to optimize. The contribution order of the transfer paths will be updated after each optimization and find the new maximum transfer path to further optimize. For example, after the reduction according to the scheme 1, the maximum path of the contribution is changed from the vertical direction of the anti-rolling torsion bar to the longitudinal direction of the air spring, so scheme 2 is that the longitudinal direction of the air spring's amplitude is reduced by 10%.

Table 5 shows the specific reduction paths, reduction ratios, corresponding target point response's overall value and overall value reduction ratios of the 12 optimization schemes according to the previous optimization rule. It can be found that when the contribution of vertical direction of the anti-rolling torsion bar and the longitudinal direction of the air spring are reduced by 27.1% and 19.0% respectively, the vertical direction of air spring becomes the major transfer path; then the vertical and longitudinal direction of core plate, the longitudinal direction of the anti-rolling torsion bar also becomes the maximum transfer path. It is possible to avoid the situation that the target point response

does not decrease after optimizing a certain path and each optimization can reduce the target point response by adopting such an optimization method. Table 5 only shows some optimization schemes, more optimization schemes can be proposed to make the overall value lower by this method. According to the overall value of the target point that you want, the appropriate transfer path optimization scheme can be obtained through this table.

Table 5. Optimization schemes

Number	1	2	3	4	5	6	7	8	9	10	11	12
Overall (m/s ²)	0.0568	0.0559	0.0551	0.0545	0.0539	0.0534	0.0529	0.0524	0.0519	0.0516	0.0511	0.0507
Reduction ratio	1.8%	3.3%	4.7%	5.8%	6.8%	7.6%	8.6%	9.4%	10.1%	10.8%	11.6%	12.3%
Paths' reduction ratio	Path1					10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%
	Path3		10.0%	10.0%	19.0%	19.0%	19.0%	19.0%	27.1%	27.1%	27.1%	27.1%
	Path4	10.0%	10.0%	19.0%	19.0%	27.1%	27.1%	27.1%	27.1%	27.1%	34.4%	34.4%
	Path6									10.0%	10.0%	10.0%
	Path10						10.0%	10.0%	10.0%	10.0%	10.0%	19.0%
	Path12							10.0%	10.0%	10.0%	10.0%	10.0%

(2) The traditional OTPA contribution analysis method only considers the influence of excitation amplitude and ignores the influence of excitation phase. Based on the OTPA contribution analysis method, this study comprehensively considers the influence of the amplitude and phase of the excitation, and analyzes the contribution of each path of the secondary suspension of the metro vehicle to the floor vibration. In the frequency range of 300~800Hz, the vertical direction of the anti-rolling torsion bar area provides the maximum contribution to the floor vibration, followed by the longitudinal direction of the air spring area.

(3) When optimizing the major transfer path, the changes in the contribution of other transfer paths should also be considered. The situation that the target response does not decrease after optimization can be avoid and every optimization for transfer paths will be effective.

Availability of data and materials

All data generated or analyzed during this research process are included in this manuscript.

Competing Interests

The authors declare no competing financial interests.

Funding

Conclusions

Based on the results described in this paper, the following conclusions can be stated:

(1) When the metro vehicles run at 60km/h, the main interior sound source is located at the floor areas. The floor vibration caused by structural excitation provides dominant contributions to the total sound power.

Supported by National Natural Science Foundation of China(U1834201) and National Key R&D Program, Key Specialities of Strategic International Science and Technology Innovation Cooperation(2016YFE0205200).

Authors' Contributions

LP put forward the method, analyzed the data and wrote the manuscript; JH and CM were in charge of the whole trial and reviewed the manuscript; JN assisted with measurements and data analyses. All authors read and approved the final manuscript.

Acknowledgements

The authors sincerely thanks to Zhihui Li, Qi wang, et al. (Southwest Jiaotong University) for their assistances in the measurements and data processing.

REFERENCES

- [1] Thompson DJ. Railway noise and vibration: mechanisms, modelling and means of control. Amsterdam: Elsevier; 2009.
- [2] Thompson DJ. On the relationship between wheel-rail roughness and rolling noise. Journal of Sound and Vibration, 1996; 193:149-160.
- [3] R Fan, Z Su, G Meng. Application of sound intensity and partial coherence to identify interior noise sources on the high speed train. Mechanical Systems and Signal Processing, 2014, 46(2014): 481-493.
- [4] Zhang J, Xiao X B, Sheng X Z, Li Z H. Sound Source Localisation for a High-Speed Train and Its Transfer

- Path to Interior Noise. Chinese Journal of Mechanical Engineering, 2019, 32(04): 178-193.
- [5] Ahlersmeyer T. Transfer path analysis – a review of 18 years of practical application. The Netherlands: Rotterdam; 2009.
 - [6] Elliott AS, Moorhouse AT, Huntley T, Tate S. In-situ source path contribution analysis of structure borne road noise. J Sound Vib 2013;332(24):6276–95.
 - [7] Plunt J. Finding and fixing vehicle NVH problems with transfer path analysis. Sound Vib 2005;39(11):12–6.
 - [8] der Seijs MVV, de Klerk D, Rixen DJ. General framework for transfer path analysis: History, theory and classification of techniques. Mech. Syst. Signal Process. 2016;217–44.
 - [9] A. Grosso, M. Lohrmann. Operational Transfer Path Analysis: Interpretation and Understanding of the Measurement Results Using Response Modification Analysis (RMA), SAE Technical Paper, 2016, 2016-01-1823.
 - [10] D. de Klerk and A. Ossipov. Operational transfer path analysis: Theory, guidelines and tire noise application. Mechanical Systems and Signal Processing 2010, 24(7): 1950-1962.
 - [11] De Sitter G, Devriendt C, Guillaume P, Pruyt E. Operational transfer path analysis. Mech Syst Signal Process 2010;24(2):416–31.
 - [12] Keizer T. Operational Transfer path analysis applied to a Ship with Multiple Engines, Gearboxes and Propellers. Euro Noise 2015:879-884.
 - [13] S. Robert. Operational Transfer Path Analysis of Components of a High-Speed Train Bogie, Chalmers University of Technology, Goteborg, Sweden, 2016.
 - [14] Gajdatsy P, Janssens K, Gielen L, et al. Critical assessment of operational path analysis: mathematical problems of transmissibility estimation. Journal of the Acoustical Society of America, 2008, 123(5):3869.
 - [15] Putner J, Lohrmann M and Fastl H. Contribution analysis of vehicle exterior noise with operational transfer path analysis. Proceed. Meet. Acoust., 19 040035, June 2-7 2013, Montreal, Canada.
 - [16] T. Mihkel. Operational Transfer Path Analysis-A Study of Source Contribution Predictions at Low Frequency, Chalmers University of Technology, Goteborg, Sweden, 2012.
 - [17] Wei Cheng, Yapeng Chu, Xuefeng Chen, et al. Operational transfer path analysis with crosstalk cancellation using independent component analysis. 2020, 473.
 - [18] Zhang J. Transfer path research of noise and vibration and its application. Beijing Jiaotong University, 2015.
 - [19] Lei P. Study of transfer path analysis to interior noise source of subway vehicle. Beijing Jiaotong University, 2016.
 - [20] Sitter G D, Devriendt C, Guillaume P, et al. Operational transfer path analysis. Mechanical Systems and Signal Processing 2010, 24(2):416-431.
 - [21] Hee-Min Noh. Contribution analysis of interior noise and floor vibration in high-speed trains by operational transfer path analysis. 2017, 9(8):6-9.
 - [22] Putner, Fastl, Lohrmann, et al. Operational transfer path analysis predicting contributions to the vehicle interior noise for different excitations from the same sound source. International Congress & Exposition on Noise Control Engineering, 2012.
 - [23] Lohrmann M. Operational transfer path analysis: Comparison with conventional methods. The Journal of the Acoustical Society of America 2008, 123(5):3534.
 - [24] B Rafaely. Plane-wave decomposition of the sound field on a sphere by spherical convolution. The Journal of the Acoustical Society of America, 2004, 116(4): 2149-2157.
 - [25] Z G Chu, Y Yang, Y S He. Deconvolution for three-dimensional acoustic source identification based on spherical harmonics beamforming. Journal of Sound and Vibration, 2015, 344(2015): 484-502.

*Corresponding author: School of Mechanical Engineering, Southwest Jiaotong University, No. 111, North Section of 2nd Ring Road, Chengdu, Sichuan 610031, People's Republic of China.

Tel: 13551858522

Email: hanjian@swjtu.edu.cn

Figures

Figure 1

Photograph of the interior sound source identification

(a) 60km/h

(b) 80km/h

Figure 2

The interior sound source identification results

Figure 3

The narrow-band diagram of the floor vibration

Figure 4

The simplified model

Figure 5

The transfer function of a path

Figure 6

The vector diagram of the transfer paths at 200Hz

Figure 7

The flow chart of transfer path analysis

Figure 8

Reference points location diagram

Figure 9

Frequency spectrum of passenger room noise above bogie

(a) 315Hz

(b) 400Hz

(c) 500Hz

(d) 630Hz

Figure 10

The interior sound source identification results at 60 km/h

(a) calculated

(b) Measured

Figure 11

Comparison between calculated and measured value of target point

Figure 12

The overall value of the transfer paths' contributions

(a) Amplitude

(b) Phase

Figure 13

The amplitude-frequency and phase-frequency relationship

Figure 14

The contribution of secondary transfer paths

Figure 15

The change of contribution