Research on Theories and Methods of Vehicle Sound Source Recognition

Jianqiang Xiong
School of Mechanical and Electrical Engineering, Xinyu University, Xinyu, China
544029003@qq.com

Abstract. In this paper, the theory of vehicle noise source identification is studied and analyzed, based on the theory of various noise sources identification, the theory of vehicle noise source identification is divided into traditional noise source identification method, signal analysis-based noise source identification method and visualization-based noise source identification method. The basic principle, process, advantages and disadvantages of the three kinds of noise source identification theory described in this paper, as well as the application and selection analysis of the suitable situation are mainly described. Finally, it is pointed out that the application of visualization technology will be the main development trend of vehicle noise source identification theory.

1. Introduction
The main purpose of vehicle noise source identification is to identify the location of the noise source and its proportion in the total noise contribution of the vehicle, and to analyze the characteristics of the noise source category, frequency, sound intensity distribution, transmission routes and change law. Many researchers have studied the theory of vehicle noise source identification, and proposed a variety of noise source identification methods. According to the basic principle of noise source identification method, this paper divides it into the following categories: traditional vehicle noise source identification methods, which mainly include sound pressure method, sound intensity method, subjective evaluation method, selection operation method, selection coverage method, surface strength method and vibration velocity method; Noise source identification methods based on signal analysis include wavelet analysis, coherence analysis, analytic hierarchy process, frequency analysis, time-frequency domain analysis and cepstrum analysis; Noise source recognition methods based on visualization technology mainly include acoustic holography methods which represent the characteristics of noise sources in the form of graphics and images [1, 2, 3].

2. Traditional noise source recognition methods

2.1. Sound pressure methods

2.1.1. Near-field measurement. Sound level meter microphone used in the near-field measurement method is close to the surface of the part under test [4]. The purpose of near-field measurement is mainly to reduce the noise radiation interference of the part not under test. If the microphone keeps a fairly close
constant distance from the surface of automobile part and scans along the surface points in turn, the maximum noise radiation area and magnitude on the radiation surface can be found, and the main noise source location can be given by the measured sound pressure level. Near-field measurement method is simple and feasible, which is suitable for the analysis of medium and high frequency noise on large-scale surface. However, when other noise sources are tested in the reverberation sound field, the accuracy of the measured sound pressure level data is poor.

2.1.2. Through-tube measurement. The method of through-tube measurement is to measure the sound pressure level of noise source components by using the through-tube whose cross-sectional area gradually changes so that its large end is close to a certain sound source and its small end is close to the microphone of the sound level meter [5]. The main noise source can be determined by the measured sound pressure level. In order to prevent external noise from entering the pipe, the through-tube is usually made of dense material and adhered with sound absorbing material to prevent sound reflection inside. Besides using sound insulation and sound absorbing material, the structure of the through-pipe must also be checked that the sound wave in the through-tube is approximate to a plane wave. Compared with the near-field measurement method, the through-tube measurement method can effectively reduce the external noise interference, so its detection accuracy is higher than that of the near-field measurement method.

2.2. Sound intensity method
Sound intensity method uses a two-point sound pressure gradient integral to approximate the vibration velocity of air particles, and uses FFT to realize real-time measurement of sound intensity. This method cannot only obtain the sound energy of a point in the sound field, but also obtain the direction of sound energy flow at that point, and can resist the interference of other noise sources in all directions. The special acoustic environment such as reverberation chamber and anechoic chamber is not necessary for sound intensity measurement. In general acoustic environment, even in the case of interference noise, the sound power of a sound source can be accurately obtained by sound intensity measurement [6, 7, 8]. Sound intensity measurement is very suitable for measuring complex noise sources. Sound intensity method can separate the sound power of these components or systems and calculate the sound power separately. However, this method is only suitable for identifying steady and static noise sources, and the special dual sound intensity probe is expensive.

2.3. Subjective evaluation method
Subjective evaluation method is to determine the location and characteristics of the noise source when the vehicle is running according to the long-term accumulated experience of the inspectors [9, 10, 11]. According to the actual situation, vehicle noise can be defined into several different levels, and the level definition can be shown in Table 1.

| Level | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|-------|----|----|----|----|----|----|----|----|----|----|
| Opinion | Unacceptable | Transition stage of acceptance | Acceptable |
| Object of acceptance | All customers | The vast majority of customers | More critical customers | Trained people |

Because subjective evaluation method is easily influenced by human factors, it is difficult to give quantitative evaluation data for noise sources. Therefore, this method is only suitable for simple noise source recognition.

2.4. Selective operation method
Selective operation method is to separate automobile parts and components according to measurement requirements step by step, measure component noise level one by one, and then calculate the proportion of total noise level in the overall operation of the automobile according to the acoustic superposition
principle, so as to determine the main noise source of the automobile [12]. This method is simple, intuitive and does not need advanced equipment, it is suitable for dense noise recognition. The disadvantage is that each component is an interrelated whole, and the removal or stopping of a part will affect the related parts, so the error of measured noise data is large.

2.5. Selective coverage method
Cover the machine with a cover made of sound insulation material with the same shape as the part under test, and then expose only one part at a time for measurement, then cover again after measurement, and then determine another part according to this method [13]. The advantage of selective coverage method is that as long as the covering is tight and the sound insulation effect is good. High accuracy can be achieved. The disadvantage is that the coverage is not easy to seal tightly, which will affect the measurement results, especially the isolation of low-frequency noise is difficult, so it is only suitable for the measurement of medium and high-frequency sound sources in vehicles.

2.6. Surface Strength Method
This method uses accelerometer to measure the normal vibration velocity of the vibration surface and regards it as the vibration velocity of the air particle in the sound field close to the vibration surface. A microphone is placed near the accelerometer to sense the sound pressure signal. The surface sound intensity is obtained by multiplying the above two signals [14, 15]. The advantage of this method is that the information of sound intensity and surface vibration velocity can be obtained simultaneously, which is convenient for the calculation of sound radiation efficiency. The disadvantage of this method is that it has a large workload and is not suitable for rotating parts and high temperature parts.

2.7. Vibration velocity method
Vehicle structural vibration causes noise, and the vibration velocity of the structure surface has a certain function relationship with radiated noise. The surface vibration velocity method is based on this principle to identify noise sources [16].

\[
W_r = \rho_c \cdot S \bar{v}^2 \sigma_r
\]  

In the above formula, \(W_r\) is the radiated sound power of the vibration surface; \(\rho_c\) is the air characteristic impedance; \(S\) is the area of the vibration surface; \(\bar{v}^2\) is the time average of the mean square value of the normal vibration velocity of the particle; \(\sigma_r\) is the acoustic radiation coefficient of the vibration surface. If the surface of sound source is divided into several small pieces and the vibration velocity of each small area is measured, the equal vibration velocity curve of the surface of sound source can be drawn, it can visually express the sound energy and the strongest radiation point of each point on the surface of sound radiation, this method does not need special acoustic environment, but the disadvantage is that a large number of data need to be measured and calculated.

3. Noise source recognition methods based on signal analysis
Signal analysis method uses detection equipment to measure the noise source, and to analyze the measured noise source signal, to clarify the frequency characteristics of the noise source signal, noise categories and the relationship between the various noise signals, so as to recognize the noise source.

3.1. Spectrum analysis
Spectrum analysis is based on the frequency characteristics of noise to determine the main noise sources. Through the noise spectrum, on the one hand, the low, medium and high frequency distribution of noise sources can be clear, on the other hand, peak noise sources can be determined. Noise spectrum analysis can only be carried out at a single measuring point, and the main noise source analysis is relative to the whole machine equipment. Therefore, the spectrum analysis method should be combined with other noise source methods. Firstly, other noise source analysis methods are used to find the main noise source
location, and then the noise source spectrum analysis is carried out to identify the main components of the noise [17].

3.2. Cepstrum analysis
Cepstrum analysis can be used to analyze complex spectrum periodic structure, separate and extract the periodic components of dense overtone signals. Cepstrum is defined as the power spectrum of the logarithmic power spectrum [18, 19], and its expression is:

\[
C_p(q) = |F\{\log G_x(f)\}|^2
\]  

(2)

In the above formula, \(C_p(q)\) is the power cepstrum of the signal \(x(t)\); \(F\{\}\) represents the Fourier transform of the contents in parentheses; and \(G_x(f)\) is the power spectrum of the signal \(x(t)\). Cepstrum analysis method can display the periodic components of the complex side-frequency structure on spectrum, distinguish the source signal from the modulated signal, so cepstrum analysis method is especially suitable for separating a noise signal from the complex noise source to identify the noise source.

3.3. Coherence analysis
Coherence analysis uses the frequency domain coherence function to describe the proportion of the noise signal of the measured components in the total noise signal outside the vehicle. According to the results, it can be judged whether the noise is mainly generated by the components, and then the contribution of each noise source to the total noise signal can be obtained. Coherence analysis functions include constant coherence function, multiple coherence function and partial coherence function. The first two functions are used mainly for the identification of independent noise sources. When the noise sources are not independent, they can only be qualitatively described, and it is difficult to quantitatively analyze. In the case of independence and low background noise, the primary-secondary relationship of noise sources can be correctly identified and arranged by using the method of constant coherence function, while the partial coherence function can analyze the effect of various factors under the condition of multiple independent noise sources [20, 21, 22]. The advantage of the coherent analysis method for identifying noise sources is that it can analyze the characteristics of noise sources in actual working conditions without changing the acoustic environment in the field.

3.4. Time-Frequency domain analysis
Linear time-frequency analysis is based on the expansion of signals into a set of weighted frequency modulation Gaussian functions. The weighted functions describe the characteristics of signals in local time and frequency, and there is no interference between the cross-terms. Square time-frequency analysis has the highest time and frequency resolution at high frequencies, but there is mutual interference between cross-terms [23, 24]. The traditional spectrum analysis method is not suitable for processing instantaneous and non-stationary noise signals, while the time-frequency analysis method is suitable for processing instantaneous and non-stationary noise source signals.

3.5. Wavelet analysis
Wavelet transform can obtain the macro and micro characteristic information about signals. This analysis technology can replace the traditional spectrum analysis, and can analyze and process various types of signals. In wavelet analysis, different "scales" or "resolutions" can be used to observe signals, so wavelet analysis is suitable for processing noise signals in non-stationary processes [25]. The advantage of wavelet analysis is that there is no interference between cross-terms and it has high time resolution at high frequency. The use of wavelet analysis depends on frequency filtering window. In low frequency range, the window size is large, and it can accept high frequency resolution. With the increase of frequency, the size of window decreases and the time resolution increases. Wavelet analysis is especially suitable for detecting instantaneous and non-stationary broadband noise.
3.6. Analytic hierarchy process

Analytic Hierarchy Process (AHP) is based on the characteristics of noise sources and uses the theory of AHP to establish a structural model with three levels: target layer, i.e. the order of primary and secondary noise sources, represented by A; intermediate layer, i.e. frequency layer, represented by B; and the lowest layer, i.e. noise source layer, represented by C. The factors $f_1, f_2, \ldots, f_n$ in frequency layer B are the peak frequency or frequency band of noise evaluation point [26]. Analytic Hierarchy Process constructs the judgment matrix by testing the noise, judging the mutual importance of each element at each level and quantifying the scales. Scale quantization method uses a 1-9 scale method, and the criteria for judging the relative importance are shown in Table (2).

| Scale | Meaning |
|-------|---------|
| 1     | $B_i$ and $B_j$ Two factors are equally important |
| 3     | $B_i$ factor is slightly more important than $B_j$ factor |
| 5     | $B_i$ factor is obviously more important than $B_j$ factor |
| 7     | $B_i$ factor is more important than $B_j$ factor |
| 9     | Compared with $B_j$, $B_i$ is extremely important |
| 2, 4, 6, 8 | The median of the above two adjacent judgements |
| 1, 1/2, 1/3, \ldots, 1/9 | The reciprocal of the above judgment |

After the judgment matrix is established, hierarchical ranking and consistent test are carried out. Firstly, ranking between layers is carried out, i.e. finding out the maximum eigenvalue $\lambda_{\text{max}}$ and the eigenvector $W$ of the judgment matrix [B]. The component $W_i$ of $W$ is the single ranking weight of the corresponding factor $B_i$. In order to test the deviation degree of the judgment matrix [B] from the consistency matrix, the consistency index CR is introduced.

$$CR = \frac{\lambda_{\text{max}} - n}{(n-1)RI}$$

In the formula above, n is the order of the judgment matrix, $\lambda_{\text{max}}$ is the maximum eigenvalue of the judgment matrix, and CR is the revised value of the consistency index of the judgment matrix. When CR < 0.11, it is considered that the judgment matrix has acceptable consistency. Otherwise, because the judgment matrix deviates too much from the consistency, we should consider revising the judgment matrix. The total hierarchical ranking should be carried out from top to bottom, and the importance weights of all elements in this layer relative to the upper level are calculated. In the total hierarchical ranking results, the greater the weight of the sound source, the greater the contribution of the sound source to the noise of the evaluation point, thus the identification results of the noise source can be obtained.

4. Noise source recognition method based on visualization technology

Visual noise source recognition technology is to reconstruct the three-dimensional sound field of pressure, intensity and velocity surrounding the sound source surface by measuring the sound pressure on the two-dimensional holographic plane and using various reconstruction algorithms. Finally, the three-dimensional sound field is visually displayed in the form of graphics or animation.

4.1. Near-field acoustic holography

Near-field acoustic holography is to record holographic data close to the measured sound source surface, keeping the distance d between sampling plane and sound source plane far less than wavelength $\lambda$, and then reconstruct three-dimensional sound pressure field, velocity field and sound intensity field by transformation technology [27, 28, 29]. Near-field acoustic holography cannot only identify and locate noise sources, but also predict the radiation of sound sources in a sound field. Therefore, it is not only
sound source location technology superior to sound intensity measurement technology, but also a sound field measurement technology with conventional sound radiation calculation function. This method is suitable for the identification of low frequency sound source characteristics, surface characteristics analysis of scatterer structure, structural modal vibration and directional analysis of the noise source.

4.2. Conventional acoustic holography
Conventional acoustical holography refers to recording by optical photography or digital recording equipment when the distance \( d \) between the receiving plane and the object is greater than wavelength \( \lambda \) [30]. It can only record propagation components whose spatial wave number is equivalent to or less than \( 2\pi\lambda \). Three-dimensional reconstructed image of response sound field distribution can be obtained by irradiating hologram with an appropriate light source or by calculating transformation, the resolution of the reconstructed image is limited by the acoustic wavelength. Conventional holograms can only face the source of noise. Therefore, when the radiation field of the noise source is directional, the important information of the noise source may be lost. Holograms recorded by the sound pressure can only be used to reconstruct the sound pressure field, but the physical information such as vibration velocity and sound intensity cannot be obtained.

4.3. Far-field acoustic holography
Far-field acoustic holography is the distance \( d \) between the holographic recording plane and the holographic reconstruction plane, which is much larger than the wavelength of sound wave \( \lambda \) [31]. This method reconstructs the surface sound pressure and vibration velocity field by measuring the sound pressure field far away from the sound source, thus predicting the sound pressure field, vibration velocity field and sound intensity field at any point outside the radiation source. Compared with near-field acoustic holography, far-field acoustic holography has the advantages of simple calculation and easy identification of far-field contributing sources. Like conventional acoustic holography, the resolution of the reconstructed image obtained by far-field acoustic holography is limited by acoustic wavelength \( \lambda \), so it is not suitable for high-resolution acoustic field analysis.

5. Conclusion
This paper describes these basic principles of traditional vehicle noise source identification methods. Noise source identification methods based on signal analysis, noise source recognition methods based on visualization technology. The advantages and disadvantages of these three methods in noise source identification are discussed. Different kinds of noise source identification methods have their limitations. In the specific application process, noise source identification methods should be selected reasonably according to the actual situation to obtain correct and comprehensive noise source characteristics. Take into account these, appropriate noise control measures should be formulated and adopted to improve the acoustic quality of automobiles. Because visual identification technology of noise source can clearly locate and quantify the noise source, and can visually display the noise propagation path in a graphical way, it has the advantages that other noise source identification methods do not have. In recent years, with the rapid development of graphics and image analysis software and hardware technology, visualization technology has been extensively employed in the field of noise recognition. Therefore, the application of visualization technology will be the primary development trend of noise source identification theory and method.

Acknowledgments
This work was financially supported by science and technology projects of Jiangxi Provincial Education Department (GJJ161186), and science and technology projects of Xinyu City (20163090853).

References
[1] Yang, Bing. "Noise Source Identification Based on Acoustic Holography." Diss. Dalian Jiaotong University, 2013.
[2] Jia, Jide. "Study of the Key Technology and Engineering Application for the Interior and Exterior Noise Control in Coaches." Diss. HeFei University of Technology, 2007.

[3] Zhao, Xingwei., et al. "Avoiding creep groan: Investigation on active suppression of stick-slip limit cycle vibrations in an automotive disk brake via piezoceramic actuators." Journal of Sound and Vibration 441 (2019): 174-186.

[4] Bizon, K., "Analysis of Diesel Engine Combustion Using Imaging and Independent Component Analysis." Proceedings of the Combustion Institute 34. 2 (2013): 2921-2931.

[5] M. Marangoni., et al. "Second Harmonic Generation from Radiation to Guided Modes for the Characterization of Reverse-proton-exchanged Waveguides." Optics Express 12. 2 (2004): 294-298.

[6] Tanabe, Yosuke., and Inoue, Akira. "Sound intensity transfer path analysis and its application to analyze the acoustics in vehicle interior." Noise Control Engineering Journal 66. 3 (2018): 222-230.

[7] Sun, Songsong., et al. "A Study on the Noise Source Identification of Engine Based on Sound Intensity Technique." Automotive Engineering 36.1 (2014): 48-59.

[8] Lu, Yimin., et al. "Design and Experimental Verification of Modified Sound Intensity Measurement System." China Test 42.6 (2016): 60-63.

[9] Kim, H W., et al. "Sound quality evaluation of the impact noise induced by road courses having an impact bar and speed bumps in a passenger car." Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 224.6 (2010): 735-747.

[10] Tian, Jiantao., et al. "Test and Research on Classification Method of Subjective Evaluation for Construction Machinery Noise." Construction Machinery and Equipment 45.9 (2014): 25-30.

[11] Huang, Haibo., et al. "Research on the objective sound quality of vehicle suspension shock absorber abnormal noise based on EMD-WVD." Journal of Vibration and Shock 34.18 (2015): 154-160.

[12] Lin, Manqun., et al. "Noise Source Identification of Single Cylinder Gasoline Engine with Combination of Several Methods." Mechanical Science and Technology for Aerospace Engineering 35.9 (2016): 1396-1401.

[13] Liu, Shuai., et al. "A Study on Surface Radiation Noise Source Identification and Noise Reduction for Diesel Engine." Automotive Engineering 38.9 (2016): 1114-1119.

[14] Meng, Haodong. "Research on Identification Technology of Vibration and Noise Source for Small and Medium Power Diesel Engine." Diss. Nanjing University of Aeronautics and Astronautics, 2014.

[15] Cui, G X., et al. "A Study on Estimating Gasoline Engine Radiated Noise based on Surface Vibration Measurement." Applied Mechanics & Materials 694 (2014): 509-513.

[16] Zhang, Quan., et al. "Testing lawn mower noise source based on surface vibration method." Science Technology and Engineering 19.4 (2019): 74-78.

[17] Yao, Zhiqiang., et al. "Design of Noise Vibration FFT Spectrum Analyzer on 600 MW Unit Auxiliary Equipment." Instrument Technique and Sensor 2 (2017): 35-38.

[18] Wang, Ce., et al. "Comparative Study on the Contributions of Wheel Center Forces to the Vibration and Noise of Vehicle Based on Coherence Analysis." Automotive Engineering 40.1 (2018): 63-68.

[19] Li, Hong., et al. "Application of EEMD Noise Reduction and Cepstrum Analysis in Fault Diagnosis of Wind Power Bearing." Machine Tool & Hydraulics 46.13 (2018): 156-159.

[20] C. Ballesteros., et al. "Identification and analysis of the noise sources of an engine settled in a car using array-based techniques." International Journal of Vehicle Noise and Vibration 14.2 (2018): 171-190.

[21] Huang, Haibo., et al. "Vehicle Interior Noise Source Identification based on wavelet partial-coherence analysis." Journal of Vibration and Shock 37.7 (2018): 157-163.

[22] Chen, Ke., et al. "Coherence Analysis on Vibration Isolation Performance of Power-train Mounting and Vehicle Interior Noise." Chinese Journal of Construction Machinery 15.4
(2017): 354-358.

[23] Ma, Weijin., et al. "Time-Frequency Domain Analysis of an Automobile Transmission." Journal of Mechanical Transmission 41.1 (2017): 96-99.

[24] Jia, Jide., et al. "A Time-Frequency Analysis Method Suitable for Engine Vibration Signals." Automotive Engineering 39.1 (2017): 97-101.

[25] Lee, S., et al. "Improvement of impact noise in a passenger car utilizing sound metric based on wavelet transform." Journal of Sound and Vibration 329 (2010): 3606-3619.

[26] Chen, Xinrui., et al. "Noise Source Identification of Diesel Engine Based on Analytic Hierarchy Process." Automotive Engineering 32.1 (2010): 41-44.

[27] Luo, ZhongWe., et al. "Near-field acoustic holography with three-dimensional scanning measurements." Journal of Sound and Vibration 439 (2019): 43-55.

[28] Nicolas, P., and Valdivia. "Advanced equivalent source methodologies for near-field acoustic holography." Journal of Sound and Vibration 438 (2019): 66-82.

[29] Chardon, G., et al. "Near-field acoustic holography using sparse regularization and compressive sampling principles." The Journal of the Acoustical Society of America 132.3 (2012): 1521-1534.

[30] Liu, Jiawei., et al. "Acoustic source reconstruction and visualization based on acoustic radiation modes." Journal of Sound and Vibration 437 (2018): 358-372.

[31] Miao, Feng., et al. "Multi-aperture far-field acoustic holography method for improving imaging resolution." Acta Acustica 43.1 (2018): 76-82.