Acta Technica 62 No. 2B/2017, 663–672

Characteristic model based on structural noise of heavy duty vehicle engines

Jiao Hongtao[1]

Abstract. With the improvement of people's living standard, people's requirements for living environment are getting higher and higher, and their attention to noise pollution is also getting higher and higher. In order to establish the characteristic model for structural modeling of heavy duty vehicle engines, and obtain the noise reduction method, in this paper, according to take four-stroke six-cylinder diesel engine as an example, the modern design theory and method were used to conduct a comprehensive analysis to the mechanism of diesel engine noise, main radiation noise sources and so on; then, the internal combustion engine noise source identification method that was suitable for engineering practice was proposed, the surface vibration velocity level of internal combustion engine was obtained by the improved surface vibration velocity method, the contribution of radiated noise, sound power level and radiated noise of each component was predicted successfully. The final experimental results show that the proposed method which is in good agreement with the measured results can be used to predict the sound power of the engine and identify the main radiated noise source of the engine, which is very practical for the low noise design and prediction of the engine.

Key words. Heavy vehicle engine, noise, noise control.

1. Introduction

Noise can cause people's mental instability, emotional instability, resulting in headache, dizziness, insomnia and other illnesses, in serious period, it can damage people's hearing organs, resulting in noise deafness; besides, it also has a negative impact to the nervous system, the cardiovascular system, and the gastrointestinal system, etc.; noise will reduce the work efficiency; high-frequency noise causes the structural sound fatigue, so that buildings and equipment are damaged [1]. The vehicle noise is one of the main sources of ambient noise. According to the statistics, the average of heavy-duty vehicles is 100 dB (A), the public transport is 90 dB (A), and the maximum noise that a person can bear in the car compartment is 70 dB

[1]Zhengzhou Railway Vocational & Technical College, Henan, Zhengzhou, 450052, China

(A). If the noise generated by the vehicle reaches a certain intensity, it will cause that the driver's auditory sense suffers long-term stimulation, this will not only significantly reduce the auditory organ sensitivity, but also produce uncomfortable feeling and impatience, tension and other negative emotions, thus affecting traffic safety, resulting in the hidden dangers of life and property of the people [2]. In addition, the noise can also make people's vision change abnormally, in the role of 90 dB (A) noise, the sensitivity of human eyes to distinguish the brightness will be reduced, and the reflect time to identify low light will be lengthened; then, 85-110 dB (A) noise can magnify people's pupil; 112–120 dB (A) of the stable noise can also reduce the stability of vision clarity. Noise affects the normal feeling of the visual system through the human auditory system, which will undoubtedly bring great risks to traffic safety [3]. The engine noise source is analyzed and researched by using the analytic hierarchy process (AHP) and the cluster analysis method. According to combine with the experiment, the contribution of engine's noise in the center frequency of the 1/3 octave frequency within the working speed range is analyzed, and the contribution of each component to important frequency segments is also analyzed, moreover, the weight index value is given, which provides specific quantitative indicators for the future of low-noise engine design [4]. In the test case, the noise sources that their noise contribution to the machine is located in the top three are oil pan, air inlet and intake pipe. Especially in the idling conditions, the radiation noise of the oil pan occupies part of the total noise, which should be an important part of engine noise reduction, thereby improving the whole machine noise. On the basis of surface vibration test and sound intensity test method, the contribution of sound power contribution is analyzed. The results of this study can show the contribution of component radiated noise to the noise power of the whole machine, which provides quantitative guidance for the improvement design of the low noise in diesel engine engineering [5].

2. State of the art

Whether there's good vibration, noise, running smoothness is one of the key factors to determine the excellent performance of internal combustion engine. Since 1950s, the vibration and noise problems of the internal combustion engine have begun to be studied deeply abroad. According to start from the vibration and noise sources of an internal combustion engine, the mechanism of their generation, transmission and radiation is analyzed, and the classification analysis on the noise of internal combustion engine is also carried out [6–7]. From the end of 1960s to the end of 1970s, with the introduction of noise standards in various countries, the research focused on the study of combustion noise, the distribution of surface noise radiation in an internal combustion engine, the noise reduction effect of various special materials, and the improvements in the traditional structure of an internal combustion engine, etc. From the 1980s onwards, with the development of computer science and mechanics, modern analysis and calculation methods and test methods have been widely cited in the vibration and noise analysis of internal combustion engine, and then, there has been a phenomenon of using finite elements, boundary element technology to calculate and analyze the internal combustion engine vibration and noise problems, besides, the sound intensity method has also been used to measure near-field noise, etc., and a lot of results have been made at the aspects of the vibration and noise prediction [8]. Since the 1990s, the research of vibration and noise of internal combustion engine has entered a new stage. And the concept of new concept design and the technical direction of subjective evaluation of vehicle sounds are put forward. Then, the combination of virtual prototyping design and test technology is carried out to control the structural vibration and noise [9]. With the continuous development of related technologies and the constant improvement of requirements of people on the internal combustion engine vibration and noise, the future car noise target is to reach 71 dB (A).

3. Methodology

3.1. Study on the relationship between surface vibration and radiated noise of diesel engine

1/3 octave band analysis is well fit for noise analysis of rotating machinery, because it does not involve the directional effect of noise. If a large rigid piston (that is, the piston vibrates at the same phase) vibrating on an infinite baffle is considered, and the size of the piston is very large, in this case, the direction of the radial sound of a vibrating piston is perpendicular to its surface, the acoustic power that the piston radiating enters into the surrounding medium is expressed as the force multiplied by the speed, and then multiplied by the area, as shown in the formula

$$W_{\mathrm{rad}} = \pi a^2 p_{\mathrm{rms}} u_{\mathrm{rms}} \,. \tag{1}$$

Here, p_{rms} is the root mean square radiation pressure of a point in space, u_{rms} is the corresponding root mean square velocity at the same point and a is the radius of the piston.

From the acoustic pressure equation it can be obtained, $p = u\rho_0 c$, thus, the calculation formula can be obtained in the form

$$W = \rho_0 c S \left\langle \bar{u}^2 \right\rangle \,. \tag{2}$$

Here, $S = \pi a^2$, $< >$ represents the time average and "" represents the space average.

The above derivation is based on the ideal state, and an arbitrary structure of the acoustic radiation takes this as a comparison. Thus, the radiation ratio σ of any structure is defined as the acoustic power of a structure radiating into half space (i.e., the side of the structure) that is it divided by the sound power radiated by a large piston with the same surface area and the same root mean square velocity as the structure. Thus, the radiation ratio can be used to describe the efficiency of acoustic radiation. When compared with the same area of the piston, the structure radiates the sound by this efficiency, that is, the piston has a radiation ratio that it's 1. So for any structure, a formula for calculating acoustic power of structural radiation is shown in the relation

$$W_{\mathrm{rad}}(f) = \rho_0 c S_{\mathrm{rad}} \sigma_{\mathrm{rad}}(f) < U_0^2(f) > \ . \tag{3}$$

The mean square velocity by area average is actually the mean square value of the normal vibration velocity of the vibration surface. The radiation ratio provides a strong relationship between the structural vibration and the associated radiated sound power. Then, the mean square value of the normal vibrational velocity of the sound radiation surface of vibrating object can be obtained by experiment or theoretical calculation. If the value or relationship of the radiation ratios of different types of structural units can be established, the noise radiation can be estimated to establish the relationship between structural vibration and radiated noise. The radiation ratio $\sigma_{rad}(f)$ value in the formula is in the range between 1–2.

$$W_{\mathrm{rad}}(f) = \frac{p^2(f)}{\rho_0 c} S_{\mathrm{trav}} \ . \tag{4}$$

In the above formula, S_{trav} is the surface area of a spherical surface of the acoustic sensor, then, the measured pressure level from the sound source r can be expressed in formula

$$p^2(f) = (\rho_0 c)^2 \left(\frac{S_{\mathrm{rad}}}{S_{\mathrm{trav}}}\right) \sigma_{\mathrm{rad}}(f) < U_0^2(f) > \ . \tag{5}$$

Formula (5) is represented in logarithmic form, as shown in the equation

$$\mathrm{SPL}(f) = L_{\mathrm{v}}(f) - 101 \log_{10}\left(\frac{S_{\mathrm{rad}}}{S_{\mathrm{trav}}}\right) + 101 \log_{10} \sigma_{\mathrm{rad}}(f) + K. \tag{6}$$

For each 1/3 octave band, the sound pressure level is calculated as shown in the following formula

$$\mathrm{SPL}(f) = L_{\mathrm{V}}(f) - 101 \log_{10}\left[\pi\left(\sqrt{\frac{S_{\mathrm{rad}}}{2}} + 2\right)^2\right] + 101\ \log_{10} \sigma_{\mathrm{rad}}(f) + 138 \tag{7}$$

and is given in dB.

The total sound pressure level is obtained by adding the sound pressure levels of each of the 1/3 octave bands. The main noise frequency of the diesel engine falls between 500–3000 Hz, so that the total noise level can be properly represented by the A-weighted sound level. For this reason and the size of the engine, the noise radiation ratio can be regarded as 1 unit, that is, $101\ \log_{10} \sigma_{\mathrm{rad}}(f) = 0$, in this case, the radiated noise generated by the engine surface is determined using by one of the formula

$$\mathrm{SPL}(f) = L_{\mathrm{V}}(f) - 10 \log_{10}\left(\frac{S_{\mathrm{trav}}}{S_{\mathrm{rad}}}\right) + 138\,\mathrm{dB},\ [L_{\mathrm{V}}(f)_{\mathrm{ref}\,0.39\,\mathrm{m/s}}] \tag{8}$$

or formula

$$\mathrm{SPL} = L_{\mathrm{V}}(f) - 10\log_{10}\left(\frac{S_{\mathrm{trav}}}{S_{\mathrm{rad}}}\right) - 33.7\,\mathrm{dB},\ [L_{\mathrm{V}}(f)_{\mathrm{ref\ ln\,m/s}}]\,. \tag{9}$$

Here,

$$S_{\mathrm{trav}} = \pi\left[\left(\frac{S_{\mathrm{rad}}}{\pi}\right)^{\frac{1}{2}} + 2\right]^2,\ L_{\mathrm{V}}(f)_{\mathrm{ref\ ln\,m/s}} = L_{\mathrm{V}}(f)_{\mathrm{ref\,0.39\,m/s}} + 172\,\mathrm{dB},.$$

Therefore, as long as the average vibration speed level based on the area average $L_{\mathrm{V}}(f)$ is calculated accurately, the sound power of the components and the whole machine radiation noise can be calculated, so that the contribution of components to the whole machine noise power can be derived.

3.2. Identification of main radiated noise sources of diesel engine by surface vibration velocity method

The identification research of the main radiated noise source of diesel engine is carried out by using the surface vibration velocity method. Then, the test uses the surface vibration test and analysis system, as shown in Fig. 1, which mainly includes piezoelectric crystal accelerometer, LMS SCADA3 acoustic vibration test and analysis system and the corresponding analysis software. Based on the vibration characteristics of the diesel engine, the analysis frequency is set as 4 kHz.

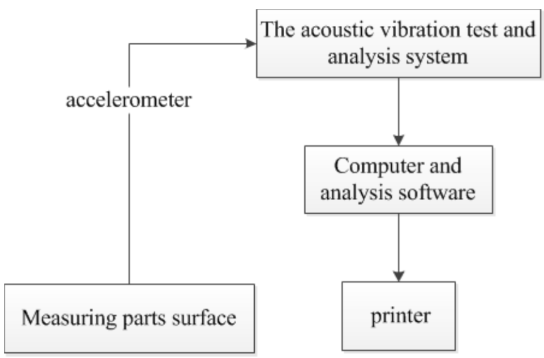

Fig. 1. Test system diagram

Surface vibration measurement uses a piezoelectric crystal accelerometer, which mainly takes into account that the accelerometer can highlight the high-frequency vibration signal, and furthermore, the actual use situation also proves the reliable performance of the accelerometer. The acceleration signal is collected and stored by the acoustic analyzer, after the compute using the software, the analysis and processing are carried out, then, the surface vibration velocity signals can be obtained after the obtained surface vibration acceleration signals are integrated in frequency domain, so that the acoustic power of each component is obtained. In the test, in order to measure the average area of the vibration acceleration, each component measures the vibration acceleration at many different locations as much as possible, and then, according to average these accelerations, the acceleration of the entire component is obtained. In order to eliminate the influence of the accelerometer weight on component vibration, a smaller weight accelerometer should be used as much as possible.

4. Result analysis and discussion

4.1. 1/3 octave spectrum of each noise radiation part of the diesel engine under four working conditions

For the 1/3 octave band, the value of 20 log 10 $(f/4)$ is shown in Table 1.

Table 1. 1/3 octave band of 20 log 10 $(f/4)$ value

1/3 octave band center frequency (Hz)	500	800	1000	1600	2000	2500	4000	5000
20 log 10 $(f/4)$ (dB)	42	46	48	52	54	56	60	62

According to the structural characteristics and surface vibration characteristics of the diesel engine prototype, the measured engine was divided into the following main noise radiating parts: air inlet (cast aluminum square pipe), intake pipe (round thin wall metal pipe), oil pan, timing gear chamber cover, exhaust pipe, body, crankcase, fuel pump and flywheel shell and other 12 parts, then the surface vibration measurement on the above parts was carried out respectively. A total of four operating conditions (idle, 1500 rpm, 1850 rpm, 2200 rpm) were tested, which were the rated speeds. Through the processing of the surface vibration data of the measuring part, the octave frequency spectrum of the noise radiating parts of the diesel engine under four working conditions was calculated. The noise radiation spectrum diagrams that take the intake pipe as an example are shown in Fig. 2–Fig. 4.

It could be seen from the spectrum that in a wide frequency range, the intake pipe had a larger radiation noise, and there was a higher value in 500–3500 Hz, which was consistent with the noise radiation frequency range of the diesel engine.

4.2. Contribution of radiation noise of components to the sound power of the whole machine

As the noise was actually a form of energy, each band of sound power could be superimposed according to the noise synthesis method, and the sound power level of components was secured, then, the components' sound power was integrated to gain the machine sound power. According to calculate the proportion of radiant noise energy of the main components in the total noise energy of the engine, the contribution of the main components to the total noise was obtained, that was, the

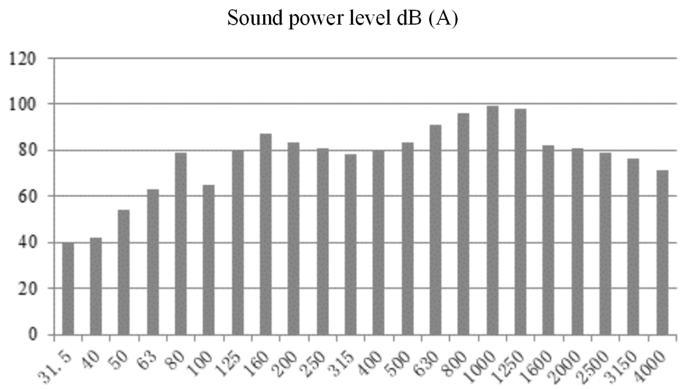

Fig. 2. 1/3 octave center frequency of intake pipe under 1500 rpm condition

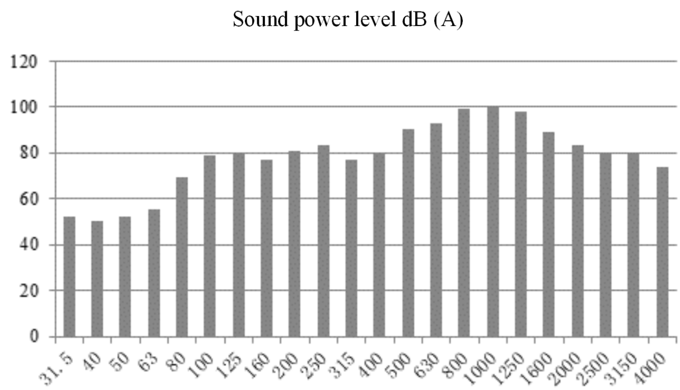

Fig. 3. 1/3 octave center frequency of intake pipe under 1850 rpm condition

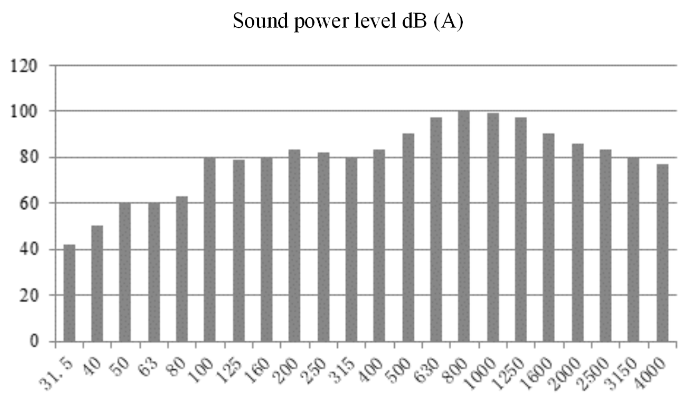

Fig. 4. 1/3 octave center frequency of intake pipe under 2200 rpm condition

order of the main noise sources of the engine. The contribution of the components of the diesel engine to the overall noise is shown in Table 2. And then, the sound power levels of the main parts in different working conditions are shown in Table 3.

Table 2. Contribution of parts of the airframe to noise radiation of the whole machine

%	Idle speed	1500 rpm	1859 rpm	2200 rpm
Oil pan	67	25	20	20
Water jacket side cover	5	7	6	4
Exhaust pipe	1	6	7	6
Valve compartment cover	3	4	6	6
Fuel pump	2	5	7	6
Air inlet	7	22	19	26
Intake pipe	10	17	20	15
The upper part of the body	2	4	4	4
Body skirt	0	0	1	1
Lower crankcase side wall	1	5	4	6
Flywheel shell	1	3	4	4
Timing gear cover	1	2	2	2

The relationship between surface vibration velocity and radiated noise was systematically analyzed. Then, the surface vibration velocity method was used to test the surface vibration of engine under four working conditions: idle speed, maximum torque point, 1850 rpm and rated speed. Among them, the calculated value of the sound power level of the whole unit integrated by the diesel engine under the rated speed condition was basically the same as that of the actual measured engine sound power level. The calculated result was 0.6–1 dB (A) lower than the actual measured result of the sound power. Analyzing the main reason: the measuring part did not completely include all the accessories of the engine, such as: air pump, pulley and generator, etc. Because the pulley was a high-speed moving part, and it is difficult to arrange the sensor on the surface. Besides, as the sensor had a certain quality, which would have a certain impact for measuring the vibration characteristics of parts, especially for some thin-walled stamping parts, however, the impact on the casting was very small.

Table 3. The power level dB (a) of the main components under different working conditions

	Idle speed	1500 rpm	1859 rpm	2200 rpm
Body	83.7	94.9	97.3	98.9
Crankcase	78.9	94.4	96.3	99.2
Air inlet	88.1	101.3	102.7	105.9
Intake pipe	90.5	100.2	102.9	103.5
Valve compartment cover	84.4	94.3	97.6	99.3
Oil pan	98.6	101.8	103.1	105
Water cover side cover	87	96.3	97.7	97.6
Flywheel shell	81.3	92.7	96.3	97.2
Gear chamber cover	79.7	89.8	92.4	94.5
Fuel pump	83.8	94.8	98.2	99.2
Exhaust pipe	81.5	95.8	98.2	99.3
Calculate the total sound power	100.4	107.8	110	112
Measure the total sound power	101	108.4	110.8	113

5. Conclusion

The internal combustion engine noise source identification method that it was suitable for engineering practice was proposed. And then, the surface vibration velocity of the internal combustion engine was obtained by using the improved surface vibration velocity method, and the sound power level of the engine radiated noise and the contribution of the radiation noise of each component were successfully predicted. Then, the method was used to predict and identify the acoustic power levels and the main radiated noise sources of the studied diesel engines, and the predictions were especially consistent with the actually measured results. In addition, the method could also be used to predict the sound power of the engine, identify the main source of radiation noise of the engine, which had a strong practicality for the low noise design and prediction of the engine. And next, the contribution of combustion noise and mechanical noise to the sound power of the whole machine under different diesel engine operating conditions was studied, meanwhile, the contribution of combustion noise and mechanical noise to the engine noise under different engine speed and load was also researched, which laid a good foundation for the adopting different noise control methods to control the sound power of the radiation noise of the whole machine.

References

[1] X. Zhang, C. Li, C. Huang: *Analysis on the role of transport equipment standardization in the development of multimodal transport.* International Symposium for Intelligent Transportation and Smart City (ITASC), Springer Nature, Book Series (SIST) *62* (2017), 139–148.

[2] C. Lim: *Railway technology of South Manchuria railway and workers in China*. The Development of Railway Technology in East Asia in Comparative Perspective, Springer Nature, Book Series (SEH) (2017), 67–103.

[3] Ö. Can, E. Öztürk, H. S. Yücesu: *Combustion and exhaust emissions of canola biodiesel blends in a single cylinder DI diesel engine*. Renewable Energy *109* (2017), 73–82.

[4] R. Powell, J. Wu, S. Gangel, C. Shue: *Total noise solution for a directional drill*. ATZ Off-Highway Worldwide *10* (2071), No. 1, 38–43.

[5] L. D. Simio, M. Gambino, S. Iannaccone: *Experimental and numerical study of hydrogen addition in a natural gas heavy duty engine for a bus vehicle*. International Journal of Hydrogen Energy *38* (2013), No. 16, 6865–6873.

[6] T. Tousignant, K. Govindswamy, G. Eisele, C. Steffens, D. Tomazic: *Optimization of electric vehicle exterior noise for pedestrian safety and sound quality*. SAE International, Technical Paper 2017-01-1889 (2017).

[7] B. Jang, J. H. Kim, S. M. Yang: *Application of rack type motor driven power steering control system for heavy vehicles*. International Journal of Automotive Technology *17* (2016), No. 3, 409–414.

[8] X. Zhao, Y. Cheng, L. Wang, S. Ji: *Real time identification of the internal combustion engine combustion parameters based on the vibration velocity signal*. Journal of Sound and Vibration *390* (2017), 205–217.

[9] S. K. Singh, S. Jain, T. Ahuja, Y. Sharma, N. Pathak: *Performance evaluation of biosignal ring for reduction of pollution level in diesel and petrol engines*. International Journal of Innovative Research in Science, Engineering and Technology *6* (2017), 13814–13824.

Received October 10, 2017