INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING Vol. 10, No. 5, pp. 59-66
10.1007/s12541-009-0094-0

Measurement and Analysis of Exhaust Noise from Muffler on an Excavator

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KEYWORDS: Noise measurement, Insertion-loss, Muffler, Exhaust noise

Through analyzing the harm of the exhaust noise from the excavator, this paper illuminated the importance of the noise measurement and analysis work,. According to some correlative measurement standards, using some instruments in hand, a set of exhaust noise measurement system especially for the excavator was designed. The exhaust engine noise from an excavator produced by a construction machinery corporation was measured and analyzed, and then, seven mufflers with different structures were designed. After analyzing the frequency spectrums of seven impedance mufflers of different structures respectively, we selected the muffler j which was of best noise elimination performance among the seven mufflers. The highest noise elimination of muffler j was up to 16.3dB, which could reduce the exhaust noise from the excavator in a larger degree. At last, we analyzed the structures and corresponding effects of noise elimination for the seven mufflers and made some important conclusions.

Manuscript received: November 14, 2007 / Accepted: September 8, 2009

NOMENCLATURE

SPL = sound pressure level
A-SPL= A sound pressure level

1. Introduction

Although there were a large amount of literatures on the analysis of severe influence of all kinds of noises on abnormal performance for many apparatus,[1-4] the noises pollution was still a serious problem in many domains. With rapid development of the city construction, the removal and building of city buildings, and the construction of basic infrastructures, directly brought the great increasing noise caused by construction machinery in most cities all over the world. It not only played an adverse part in the physiology and psychology of the workers, but also seriously affected the citizens' daily life. The long-time noise would do harm to workers' physiology and psychology, and high level noises could also damage the person's hearing and nervous system, which made persons insomnia, dreaminess and brought worse memory.[5] Diesel engine of excavator discharged a large amount of high level noise during working, for example, the inlet noise, exhaust noise, noise radiated from machine body, and gear noise. Among all above noises, the exhaust noise from engine was one of the most important noises when excavator was working, which would severely influence the complete machine performance of the excavator products. Muffler was an apparatus which was fixed on the engine to depress the inlet or output noise, So installing a muffler with high noise elimination performance on the engine was the most normal method. So, measuring and analyzing the exhaust noise level became very important for protecting the environment and improving the complete machine performance.

The noise level was an important qualification criterion for evaluating the performance of construction machinery, and had been restricted by many country laws in the world. At present, many researchers had deeply studied how to measure the noises more precisely, and they had developed a series of methods for measuring noise level. Early in 1997, R. Singh had measured the noise exhausted from mufflers with the pulse method.[6] Ling Zh-Y carried through the broadband measurement of the noise radiated from the submarine through the method of forming multi-frequency multiplication invariable beam width linear array beam.[7] Some references[8-10] acquired the acoustic characteristic of some typical noise sources by different methods.

The high level exhaust noise from the engine badly affected the complete machine performance of the construction machinery, e.g. excavator. Therefore, studying the performance of the exhaust muffler, measuring and analyzing the output noise level had become an important technique (*Noise measurement technology*), by which the exhaust noise from the excavator could be evaluated. Not only was it an important and leading technical procedure in noise controlling engineer, but also it was a method of protecting the environment and detecting whether the noise agreed with the relevant specifications or not in labor protection work.[11]

According to some correlative noise measurement standards about exhaust mufflers, using some instruments we had, we designed a set of exhaust noise measurement system especially for the construction machineries. By analyzing the noise signals collected, seven kinds of impedance mufflers of different complicated structures were designed. After analyzing the frequency spectrums of seven mufflers respectively, the muffler which had better noise elimination performance was selected.

2. Performance evaluation standards for the muffler

Transmission loss and insertion-loss were the main performance evaluation standards for mufflers. Transmission loss was the relative comparison between the entrance energy of the muffler and the exit energy, and it was the difference between the entrance sound power level and the transmission sound power level. The transmission loss, which was muffler's own attribute, was independent of pipe system and sound sources. Insertion-loss was the difference of sound power level from the sound source, before and after installing the muffler, and it was not a particular performance that a muffler own had. That was to say, the insertion-loss could only show the acoustic performance change of the whole system (muffler, pipes and noise sources included) before and after fixing mufflers, and it couldn't indicate the muffler's own noise elimination performance.

When measuring and analyzing the noise elimination performance of the muffler in practice, researchers often studied the insertion-loss. This was mainly because when the transmission loss was measured, the SPL of the entrance sound wave of mufflers needed to be measured. But the entrances of mufflers were usually inside the body of the construction machinery, which was not suitable for noise measuring. Additionally, other noise sources, radiated noise from the engine body, and noise from machine parts near the orifice of the exhaust manifold, might bring some errors for the noise measurement. So in practical measuring engineer for muffler, while evaluating and analyzing the noise elimination performance, we generally considered the insertion-loss of the muffler. Here, the insertion-loss of the exhaust muffler on an excavator engine would be measured and studied.

3. Influence of the measuring environment

3.1 Background noise and its correction

Background noise was the environmental noises existing in practical measurement, and it would still exist around when the measured noise source stopped sounding. Background noise would affect the accuracy of the measurement, so during measuring noise, we should avoid the impact of the background noise upon the measurement.

When the exhaust muffler noise was measured, owing to the influence of the background noise, the total noise level measured usually was the sum of the noise source to be measured and the background noise, which made that we couldn't directly determine the noise level of the measured object. If the difference between the background noise and the exhaust noise from engine was bigger than 10dB, the influence of the background noise could be ignored, or the amendment noise value ΔL should be subtracted from the measured engine exhaust noise.

Table 1 was a series of amendment noise values when the difference between the exhaust noise and the background noise was smaller than 10dB.

Table 1 Background noise amendment table

Difference (dB)	<3	3	4-5	6-9
Amendment (dB)	Select other quiet measure environment	-3	-2	-1

3.2 Influence of the reflected sound

Some bigger reflectors near the noise source or around the microphone would bring bigger errors, e.g., walls, grounds, mechanical equipments, and worker bodies were all reflectors. So during the course of measuring noise, the microphone should be far away from these reflectors, and one meter was the best distance. In order to reduce the influence of the reflected sound, the workers measuring noise should be lateral to the sound source. Because when the workers faced to the sound source, they would be considered as some bigger reflectors for sound wave. The sound wave reflected back would bring some impact on the measuring result. Being lateral to the sound source, the reflected area was smaller, so the impact on the measuring results would be less.

3.3 Influence of the wind noise

If the noise was measured in the presence of wind, the air flow blew onto the microphone and generated pressure change on the membrane, which would bring the wind noise and it would influence the accuracy of the measurement. Outdoor measurement should be taken place when there was no wind. If the wind force scale was smaller than 3, a windshield on the microphone should be necessary for the measurement. While the measurement shouldn't be proceeded if the measured noise strength was not big enough or the wind force scale was bigger than 3.

4. Choice of measuring essentials

4.1 Measuring time

If the environmental noise was very high, measuring the exhaust muffler noise from the excavator should be taken place when the environmental noise was minimal (e.g. late at night). This measurement was carried out in the excavator factory after work, when the environmental noise was lower relatively, so the influence on the measurement was not big.

4.2 Measuring place

During the course of noise measurement, the muffler was considered as a noise source, and the sound field nearby the machine (that was say, near-field region) was not stable. Near the machine, the position of the microphone changed a little and the sound level measured would change a lot. So we should avoid this area when measuring the noise. Outside of the near-field region there was the free-field region, where the distance between the sound source and the measuring spot increased one times, the sound pressure would decrease 6dB, so noise measurement should be taken in this field. When the measuring position was too far from the sound source but too near to some walls or other objects, the reflection would be very severe, and this region would turn into a reverberation one, where the measurement should neither be taken in such a region.[11]

In a construction machinery corporation, the characteristic of the exhaust muffler noise on an excavator was measured. There were neither anechoic room nor reverberation room, and there were also so many instruments in the assembly rooms where the transmission of the sound waves was very complicated, so the noise measurement test was taken in an opener outdoor field in the corporation, where excavator products were tested, and it could satisfy the measurement requirement for the exhaust muffler noises. The measuring spot was about 400 meters far away from the city road in front of the corporation. The test was carried out late at night, when all the noisier machines in the factory had stopped running, and with a fine and windless weather, which made sure that the impact of the air flow on the measurement could be ignored, so all above external environmental factors almost wouldn't bring too much influence on the measurement.

4.3 How to choose the measuring position

The measuring position was defined as the relative position between the sound-level meter and the exit of the muffler, and its selection was very important for the ultimate measuring result, so the measuring position must be indicated before noise measurement was taken place.

For different kinds of noise measurements, the arrangements of the measurement points were different from each other. The layout of measuring point should be arranged according to all the noise measuring specifications. Depending on these specifications,[12] when the exhaust muffler noise from the construction machinery was measured, the axis of sound-level meter should be parallel to the floor and in the same height with the exhaust orifice of the muffler. Its distance to the floor must be bigger than 1m, and at the same time 0.5m away from the exhaust orifice must be guaranteed. To keep away from the muffler outlet and air flow from mufflers, the angle between the meter and the axis of the exhaust muffler orifice should be kept 45 degrees. In addition, the distance from measuring point to the other reflectors also should be twice bigger than that to the sound source, and in order to guarantee that the sound waves were in the same incident direction, the measuring point should be kept invariant during the measuring noise course.

5. Measuring apparatus and their installation

5.1 Measuring apparatus

Sound-level meter, spectrum analyzer, automatic recorder, magnetic tape recorder, and so on, was the common noise measuring apparatus.

Sound-level meter was a sort of device which could be used to measure the SPL or sound level according to frequency weight and time weight based on the international standards, and it was the most fundamental and was used most commonly in acoustic measurement. Sound-level meter could be used to measure room noise, environmental noise, machinery noise, architecture noise and any other ones. Microphone, amplifier, weighting network, filter, attenuator and display screen composed a sound-level meter. Microphone was an electric-energy transducer which could convert the sound wave signal into electric one. Sound-level meter practically was a voltmeter reading and writing sound wave signals, and it transformed sound wave into corresponding electrical signals which could be amplified to a certain level. Then, after measuring the level, the relevant voltage could be determined according to the sensitivity of the microphone, and the frequency characteristic could be analyzed furthermore. In this measurement test, precise integral sound-level meter P&k2230 was used and it was a capacitance integral sound-level meter made by Brüel & Kjaer Corporation, which was a world-famous acoustical instrument company in Denmark.

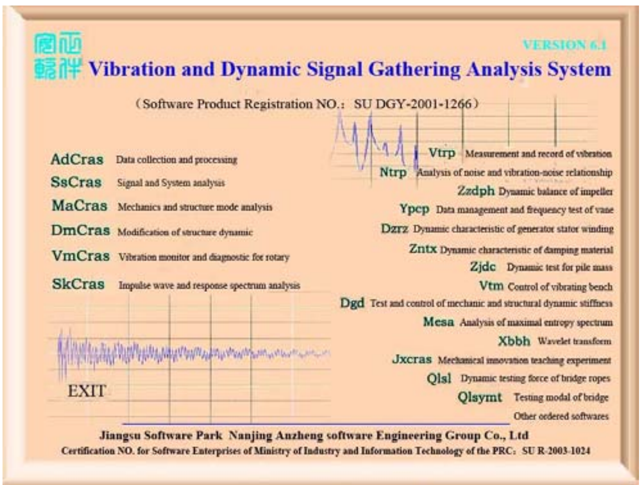


Fig. 1 Main interface of Vibration and Dynamic Signal Gathering Analysis System

Signal gathering device used was *Vibration and Dynamic Signal Gathering Analysis System (CRAS V6.1)*, which was produced by Nanjing Anzheng software engineering limited company in China. three modules, AdCras(data collection and processing), SsCras(signal and system analysis), Ntrp(analysis of correlation between vibration and noise) were mainly used. The main interface of this software was displayed in Fig. 1.

In order to shield from the interfering signals from outside, diminish the influence of noise signal outside, and guarantee the accuracy of transmitting data, shielded wires of good quality were chosen as the data wires. This system measuring exhaust noise had very good characteristic of real time and its data format could also be easily read, written and stored.

5.2 Installation of the measuring apparatus

Fig. 2 displayed the configuration scheme of noise measurement system designed. In the system, all the apparatus were connected with shielded wires according to the order of first the sound-level meter, then the signal gathering unit and at last the computer. Sound-level meter had two output interfaces, DC and AC interfaces, of which we chose the AC interface during measuring. On the signal gathering unit, there were 16 channels, of which the first one was selected. Before measuring, the sound-level meter must be adjusted and debugged. Fig. 3 showed the scene scheme of exhaust noise signals gathering system.

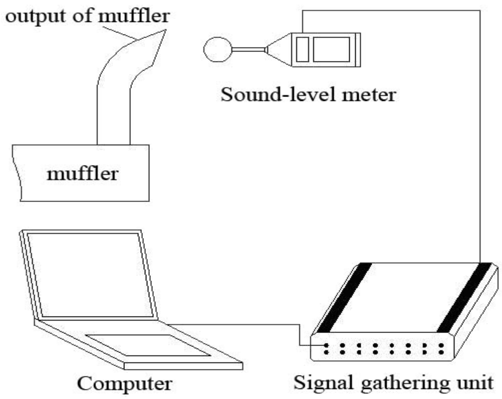
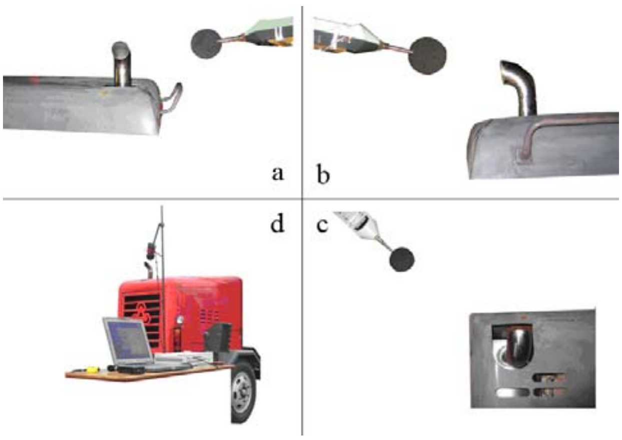


Fig. 2 Configuration scheme of noise measurement system



a Front view b Left view
c Vertical view d Full view

Fig. 3 Scene scheme of practical noise signals gathering system

6. Measurement of exhaust noise

Following installing all the measuring apparatus and laying them in proper positions according to the Fig. 2 and Fig. 3, the environmental noise first and then the exhaust muffler noise would be measured. After gathering the exhaust noise signal data for seven kinds of mufflers on the same excavator at different load speeds, the SPL of the octave frequencies band whose center frequencies were 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz would be gotten.

6.1 A sound-level formula

According to the reference,[13] the octave frequency SPL from each measuring point could be converted into A sound-level, the formula was as follows (equation (1)),

$$L_A = 10\lg\left[\sum_{i=1}^{n} 10^{0.1(L_{pi} - \Delta L_i)}\right] \tag{1}$$

In equation (1), L_{pi} was the sound level of each octave frequency band. ΔL_i was the A-weighted network amendment of the ith octave frequency band, with unit dB, and n was the number of the total octave frequency bands.

The SPL of each frequency band and total pressure level were respectively equal to the average SPL of six measurement points, and it could be presented by $\overline{L}$. The formula was as follows (equation (2)),

$$\overline{L} = 10\lg\frac{10^{0.1L_1} + 10^{0.1L_2} + \cdots\cdots 10^{0.1L_6}}{6} \tag{2}$$

In the Tables 2, it was displayed that the A-weighted network amendment from 63Hz to 16000Hz.

Table 2 A-weighted network amendment ΔL_i

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000	16000
ΔL_i (dB)	-26.2	-16.1	-8.6	-3.2	0	1.2	1.0	-1.1	-6.6

6.2 Collection of the noise signals

6.2.1 Measurement of the background noise

Late at night, the factory was in the no-production state, and there were no machines running in the corporation, when it was suitable for measuring the exhaust muffler noise from excavators. The environmental noise was very important for noise measurement, and its influence on the muffler noise results was very big, so before measuring the exhaust noise from engine, the current environmental noise should be acquired at first. Then the judgment that whether the muffler noise test should be taken or not could be given. The decibel value of octave SPL about the environmental noise measured was displayed in Table 3, and the Fig. 4 gave the noise spectrum curve of the current environmental noise. In that current measuring environment, the background noise pressure level was 51.2dB. And in the following part, some engine source noise values would be acquired to see if the environmental condition would answer for the measuring requirements. If not, another new measuring environment in other place or a later measurement in future should be taken.

Table 3 Octave SPL decibel value of the environmental noise

Frequency (Hz)	63	125	250	500	1000	2000	4000	A-SPL(dB)
SPL (dB)	-16.1	13.5	21.9	26.5	34.1	34.9	34.7	51.2

Table 4 Exhaust noise when excavator sample was in different speed unit: dB

Frequency (Hz)	63	125	250	500	1000	2000	4000	A-SPL(dB)
600 r/m	40.9	42.5	56.4	66.2	68.7	78.6	74.4	84.9
900 r/m	49.4	55.5	59.7	70.4	81.3	79.1	77.8	89.4
1200 r/m	39.1	63.4	74.4	76.1	81.5	84.6	80.8	94.4
1500 r/m	34.3	57.2	74.6	76.9	88.5	93	86.9	100.3
1800 r/m	54.8	64.7	73.6	87.6	90	94.6	92.8	102.9
2050 r/m	55.4	63	75.9	87.7	93.5	98	93.3	104.8

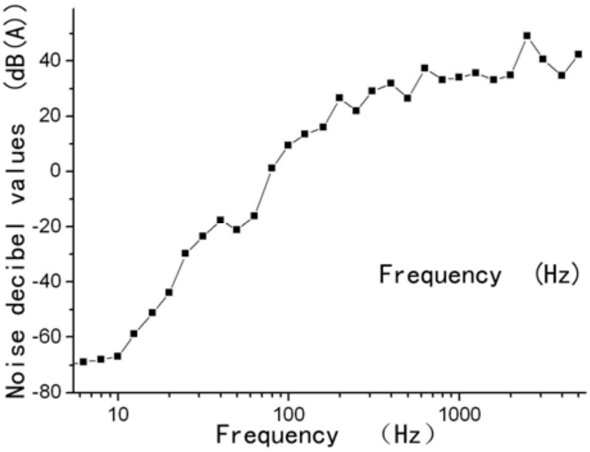


Fig. 4 One-third octave spectrum curve of the environmental noise

6.2.2 Exhaust noise measurement using substitute pipe

Weichai ZH4100 was the main engine used in this excavator sample, and the engine was four-strokes and four air-cylinders. when the engine was using the substitute pipe as the muffler, we could regard the exhaust noise values as the engine's own exhaust noise. Here, in order to find out the noise characteristic of the measured engine in detail, more kinds of speeds should be studied, and noise signals at six load speeds, 600, 900, 1200, 1500, 1800 and 2050r/m, were collected. Through analyzing and processing these noise signals, the exhaust noise and the noise spectrum curves at different load speeds for engine were given as follows, in Table 4 and Fig. 5. We could know from them that with the increase of engine load speeds, the noise values of each frequency field were all getting bigger and bigger. At the engine speed 600r/m, the A-SPL was only 84.9dB, with 94.4 dB at 1200r/m, and when the engine speed was 2050r/m, the A-SPL even reached up to 104.8dB, a very high value, which would do harm to people's health and daily life in a large degree.

We could find from all above, at six different load speeds, the difference between the background noise and the noise of each frequency band would surely be bigger than 10dB. When the load speed of the engine was the lowest, the difference was also up to 33.7dB, which was bigger than 10dB, and when the speed was 2050r/m, the difference even reached up to 53.6dB. Apparently, the impact of background noise on the result of measurement could be ignored. Therefore, here we only took the exhaust noise from engine into account.

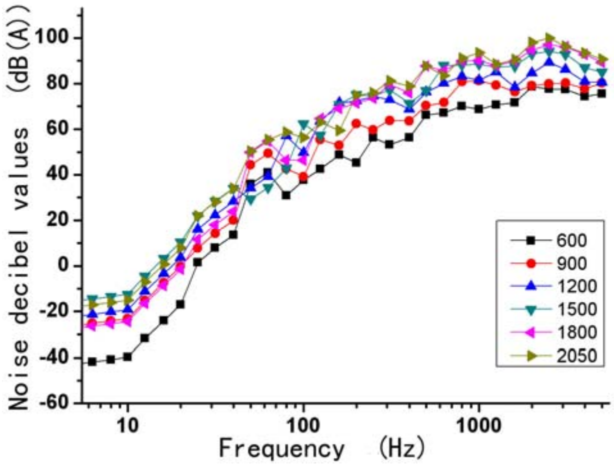


Fig. 5 Exhaust noise of the substitute pipe at variant engine speeds

From the engine noise spectrum curves (Fig. 5), we could see that in the case of low and high load speeds, the trends of the engine exhaust noise curves were generally in the same. The noise value was a little lower in low frequency, and with the increase of the frequency, the trends of the noise curves all tended to increase. Under all the load speeds, the noise decibel values were all relatively high from 100Hz to 5000Hz. At the speed of 2050r/m, the noise came to the highest value 98dB at the frequency of 2000Hz, and the total A-SPL on the measurement point also reached up to 104.8dB.

6.2.3 Measurement of exhaust noise from designed mufflers

Referring to the sound attenuation characteristic of each kind of noise elimination structure used in mufflers, we had designed *d*, *e* ...*j* seven types of mufflers of different structures for the excavator sample. After that, measurement and analysis of the exhaust noises from the seven mufflers were carried out. Fig. 6 was the structure diagrams of the seven kinds of designed mufflers, and Table 5 was their some concrete structure dimensions. In the structure diagram, the meshes represented the punched holes of different diameters on perforated pipes. Among all the seven mufflers, *f* was the only four-chamber muffler, and the others were all three-chamber ones. *e* was a typical perforated pipe muffler, and the main structure of *g* was insert-pipe, while muffler *i* was composed of insert-pipe and perforated-pipe. For muffler *d*, *f*, *h* and *j*, muffler *d* was the basic

Table 5 Structure dimensions of the seven mufflers unit: mm

Type	Number of chambers	Lengths of each chamber	Total Length	Diameter
d	3	205-146-100	451	200
e	3	146-205-100	451	200
f	4	205-146-100-50	501	200
g	3	205-146-100	451	200
h	3	205-146-100	451	170
i	3	205-146-100	451	200
j	3	205-146-150	501	200

structure, and the others were extendible ones. Compared with *d*, for muffler *f*, an expanding chamber with 50mm in length was joined after the third chamber, while muffler *h*, with its chamber only 170mm in diameter, had the same total length as *d*, and the length of muffler *j*'s third chamber was 50mm logger than that of muffler *d*. In the figure 7, there were some practical muffler samples of the seven complicated ones, and under them there was the practical substitute pipe, mentioned above, which was used to measure the engine exhaust noise signal.

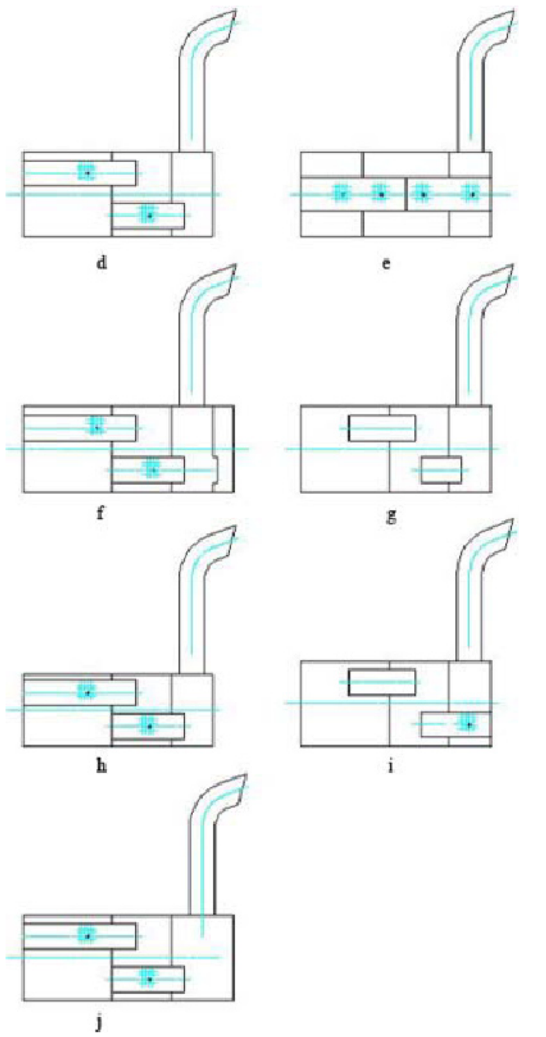


Fig. 6 Structure diagrams of the seven kinds of designed mufflers

Fig. 7 Physical diagrams of the several kinds of designed mufflers

For the seven designed mufflers of complex internal structures, the exhaust noise measurements were made. According to the practical engineering conditions, three common engine load speeds, 1200, 1800, and 2050r/m, were selected and studied. Out of the seven mufflers, the exhaust engine noises were depressed in different degrees because of their various internal structures. Fig. 8, Fig. 9 and Fig. 10 were the exhaust muffler noise curves at speeds of 1200, 1800, and 2050r/m. In the following figures, the curves *d*, *e*, *f* …j separately represented noise curves of muffler *d*, *e*, *f* …j.

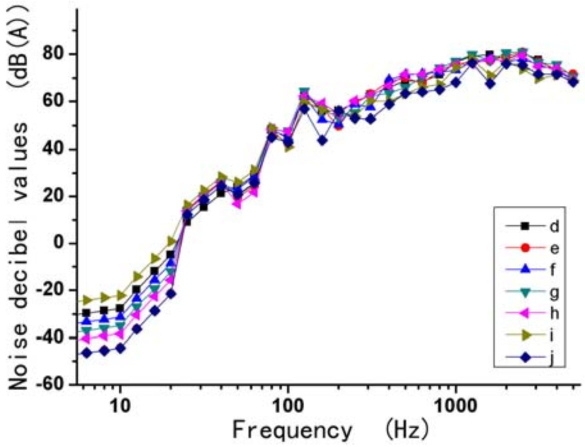


Fig. 8 Noise spectrum curves of seven mufflers at 1200r/m

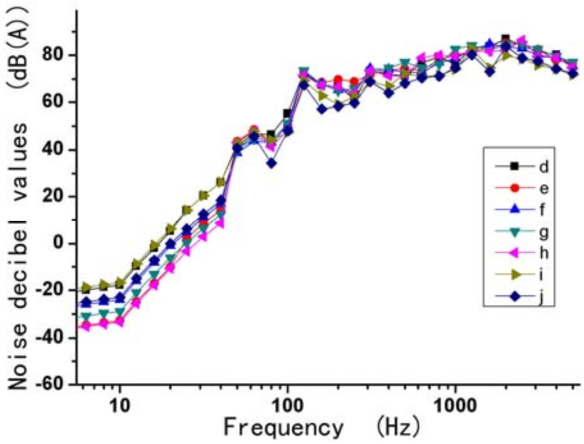


Fig. 9 Noise spectrum curves of seven mufflers at 1800r/m

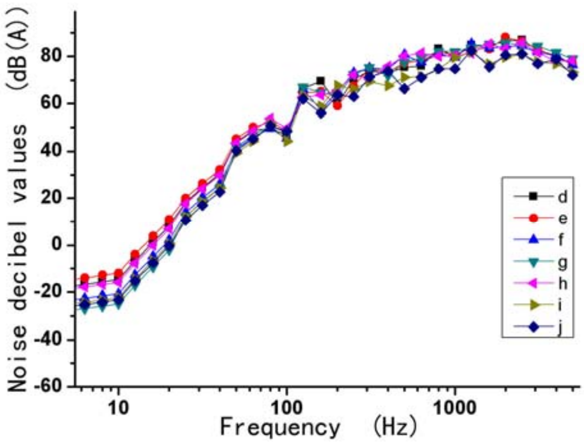


Fig. 10 Noise spectrum curves of seven mufflers at 2050r/m

From Fig. 8 to Fig. 10, we could find that, on the whole, the exhaust muffler noise curves had the same trends. At 1200r/m, the muffler *g* had the worst noise elimination with SPL 87.7dB. At low frequency, the seven noise results differed from each other very much. The muffler *i* had the worst sound elimination effect, while muffler *e* and *j* was the best. With the increase of the frequency, the noises of seven mufflers were all becoming higher and higher, and at this speed, the highest noise value was 80.8dB for muffler *e* at frequency 2500Hz. In the high frequency, the exhaust noise level of muffler *j* was the lowest, then was muffler *i*. For the whole frequency, from low to 5000Hz, the noise elimination effect of muffler *j* was the best. At 1800r/m, muffler *i* still had bad effect at low frequency and better effect at high one, and its SPL at this speed was the lowest. The highest SPL was 87dB at 2000Hz for muffler *e*. When the load speed was 2050r/m, the noise level was even higher. At low frequency, for the seven mufflers, the difference of sound levels had been smaller than those at 1200 and 1800r/m. Muffler *j* was the best one of the seven samples with SPL only 88.6dB.

According to the definition of the insertion-loss for mufflers, at three major load speeds, the amount of noise abatement of each muffler could be attained. In figure 11, 12 and 13, there were the comparison curves of insertion-loss for the seven kinds of mufflers at three major load engine speeds. And the insertion-loss curves of them at three speeds were displayed in Table 6.

Table 6 The insertion-loss of seven mufflers at three speeds unit: dB

Load speed	d	e	f	g	h	i	j
1200 r/m	7.2	7.6	8.7	6.7	8.4	10.9	12
1800 r/m	10.4	10.9	11.6	10.5	11.3	15.4	14.9
2050 r/m	11.1	11.2	12	11.1	12.1	16.2	16.3

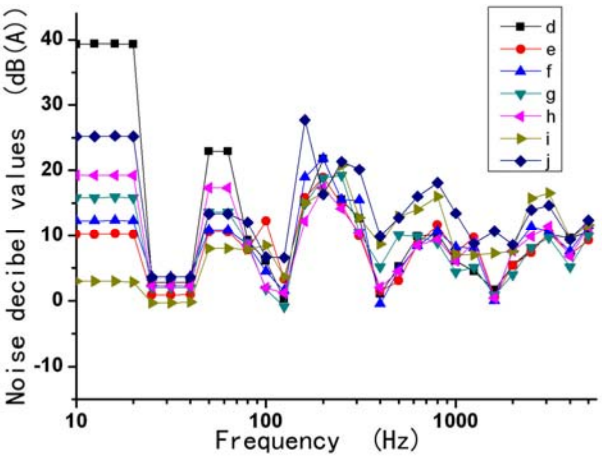


Fig. 11 Insertion-loss curves of seven mufflers at 1200r/m

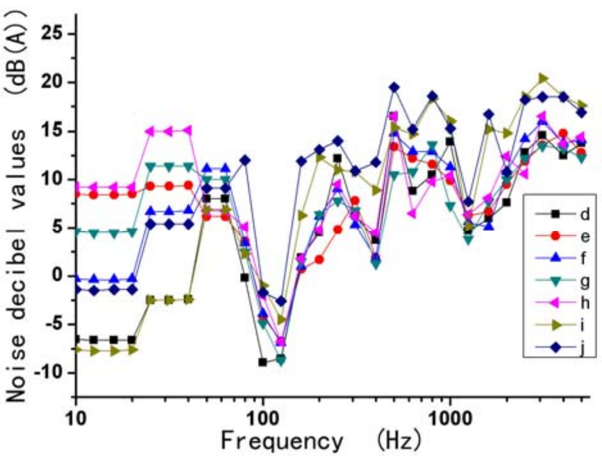


Fig. 12 Insertion-loss curves of seven mufflers at 1800r/m

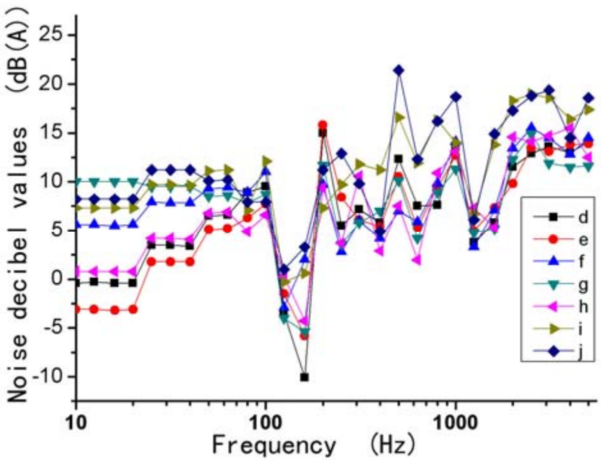


Fig. 13 Insertion-loss curves of seven mufflers at 2050r/m

From above figures and table 6, we could find that for each muffler, with the increase of the load speed, the insertion-loss was turning higher and higher. At the load speed of 1800r/m, the noise elimination of the muffler *j* was a little worse from 0Hz to 100Hz and except that, it was a good one. In the all seven kinds of mufflers, muffler *j*'s noise elimination effect was the best, and respectively reached up to 12, 14.9and 16.3dB at the three speeds, and then was muffler *i*, with noise elimination 10.9, 15.4 and 16.2dB. There were no perforated pipes in the muffler *g*, so its noise elimination effect was the worst. This was because that perforate pipe muffler had good noise elimination characteristic for high frequency. However, for muffler *g*, in the low frequency, the noise elimination effect was relatively good because of the existence of the expanding chamber. For muffler *j* and *i*, the perforated pipe structure was good one for depressing the high-frequency noise, while the expanding chamber which was 50mm longer in the third chamber for muffler *j*, and the insert-pipe for muffler *i,* reduced the low-frequency noise. All above which brought muffler *j* and *i* better noise elimination in whole frequency at three speeds.

In conclusion, the effects of muffler *i* and *j* were better, and muffler *j* was the best, while *g* was the worst. For all the seven mufflers, comparatively speaking, for three load speeds and whole noise frequency, muffler *j* had a relatively stably better effect of noise elimination.

7. Conclusion

Through the above comparisons and analysis of the noise elimination effects at different speeds for each kind of muffler, we could find that for some ones of seven mufflers, the effects of the noise elimination were relatively good, and the gap in the effect of noise elimination was not great. In summary, we could conclude that, not only at low speed but also at high speed, the noise reduction of the muffler *j* was all better, and its effect of noise elimination in whole frequency among seven mufflers was the best.

Besides, by making comparison and analysis of the structures, for seven kinds of mufflers at different load speeds, we also found, among the structures, the perforated pipe structure played a very important part in eliminating high frequency noise for impedance muffler, however, expanding chamber and insert-pipe did good at depressing the low frequency noise. So when designing the mufflers, we should consider the whole frequency distribution of noise source signals, evaluate the characteristic of all the noise elimination structures, and design structure-mixed impedance mufflers with good performance.

Through studying noise properties at different load speeds, we also concluded that, for a muffler, with the increase of load speeds, both SPL and insertion-loss of the muffler would be getting bigger and bigger.

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