Ultra-low Noise Hydraulic Excavators Using a Newly-developed Cooling System (iNDr)

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Reducing noise from construction machinery is important in creating a comfortable environment for residents near construction sites and for operators and workers. This is particularly so because an increasing amount of construction is being carried out in urban areas and at night. This article describes a newly-developed ultra-quiet hydraulic excavator that incorporates a patent-pending integrated Noise and Dust reduction (iNDr) cooling system. This excavator has achieved a sound power level that is 5dB lower than the most stringent restriction level set by the Japanese Ministry of Land, Infrastructure, Transport and Tourism. The excavator has been launched as one of our general-purpose models.

Introduction

Lately, there has been a more urgent call for the noise reduction of construction machinery because an increasing number of construction projects are being carried out at night in urban areas, and the environment must be improved for residents near construction sites and for operators. Noise reduction has become an important issue for the manufacturers of construction machinery.

Accordingly, regulations for noise abatement are issued and tightened every year. In Japan, the Ministry of Land, Infrastructure, Transport and Tourism established a type designation system for low noise construction machinery and set the criteria for low noise and super-low noise construction machines. The super-low noise level is even 6dB lower than the low noise level. In Europe, the distribution of machines that emit noise exceeding the EU noise regulation value is not allowed, and the regulation values are becoming more stringent every year. China is enacting noise regulation this year (2012).

Fig. 1 shows the noise regulation values for hydraulic excavators in Japan and Europe. The noise evaluation is standardized according to the sound power level (PWL), which indicates the total acoustic energy emanating from the sound sources of a machine. Progress has been made in the reduction of machine noise in order to comply with both the Japanese and EU regulations, increasing the number of construction machines designated as the super-low noise type. The trend for lower noise machines is expected to escalate.

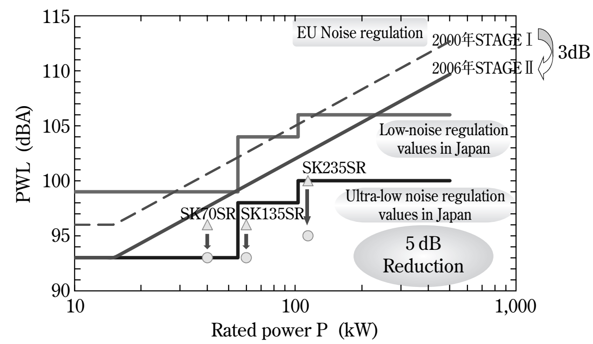


Fig. 1 Noise level of new SR series and noise regulations

Another important consideration, in addition to that of noise level reduction, is sound quality. Sound is perceived quite differently by different people, or by the same people at different times and in different situations. The sounds made by construction equipment are a major cause of environmental deterioration perceived by local residents. For the operators of the machines, however, noise can be a source of information that aids in understanding the condition of the equipment. Thus, it is important to consider the creation of an acoustic environment that causes no discomfort to the local residents and enables operators and surrounding workers to work safely and efficiently without undue tiredness.

In this context, we have developed a series of general-purpose hydraulic excavators, the ACERA Geospec SR series, for urban projects. This machine has a noise level that is 5dB lower than that required by the super-low noise standard, the most stringent standard set by the Ministry of Land, Infrastructure, Transport and Tourism. The feature has made the series stand out from the products made by other companies.

There were two approaches taken in the development of the series. One was to reduce the level of the noise, as the level significantly contributes to its obnoxiousness. The other was to pursue a quality of sound that would create less discomfort. The quality of the sound tends to deteriorate with a reduced noise level. This paper introduces the development of the Integrate Noise & Dust Reduction cooling system (hereinafter, "iNDr") as an example of this improvement.

1. Hydraulic excavator sound sources and their features

Fig. 2 depicts the structure of a hydraulic excavator. Also shown are the major sound sources in the excavator. A hydraulic excavator has a diesel engine, which drives a hydraulic pump that sends pressure oil via control valves to actuate hydraulic cylinders and motors. The engine is placed in an enclosure with a fan, hydraulic pump and air cleaner. The enclosure has an opening from which the sound emanates. The term "enclosure", as used herein, refers to the casing enclosing the sound sources.

The major sound sources include the fan, engine, hydraulic devices (e.g., hydraulic pump and control valves), slewing gear and caterpillar treads. The engine emits sounds of mechanical origin, as well as intake and exhaust noise. Construction work itself generates impact and rattling noises. The amount of noise contributed by these factors varies, depending on the size of the excavator and the working conditions. **Fig. 3** shows an example of the sound source contributions of a mid-sized hydraulic excavator at work. The contributions of the five sound sources categorized in the figure were determined by insulating the individual sounds. The inner pie chart shows the contribution in energy ratio of each sound source, while the outer pie chart shows the contributions from the enclosure opening and other sources.

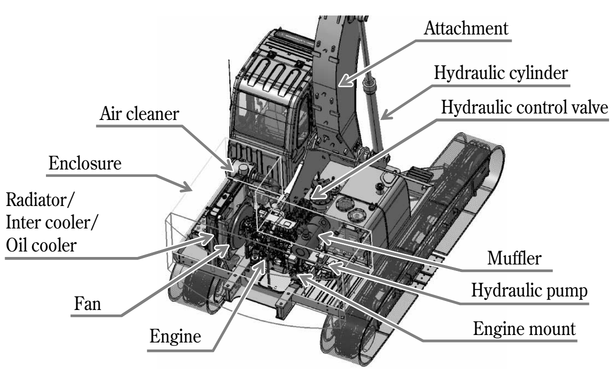


Fig. 2 Main noise sources of hydraulic excavators

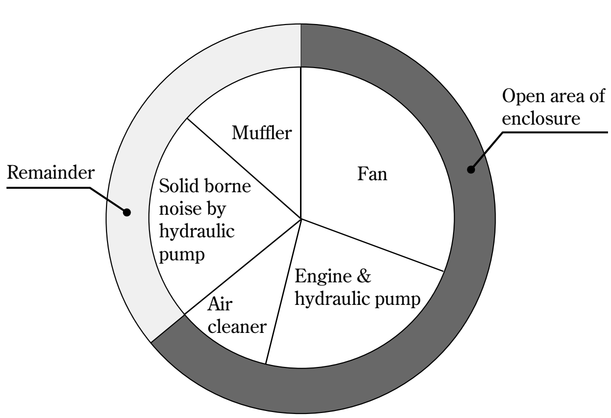


Fig. 3 Ratio of measured sound power of main sources

Unlike an automobile, a hydraulic excavator is used for stationary work at high engine load without stream wind. This invariably requires the high rpm rotation of a cooling fan, which makes the fan a significant sound source. During work, the power source becomes subject to a high load, which abruptly increases both the mechanical sound of the engine and the hydraulic sound. This amplifies the level fluctuation and adversely affects the sound quality. Solid-borne sound is caused by pulsations of the hydraulic devices and is propagated and emitted, not from the enclosure, but from other parts such as the frame and any attachment.

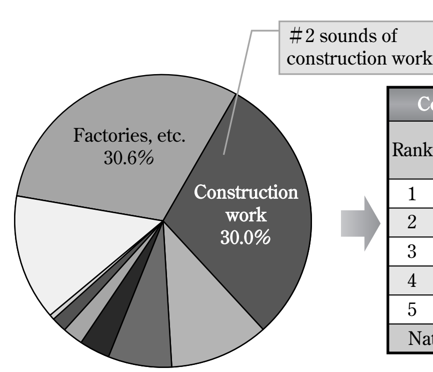
The sounds emanating from the engine and hydraulic pump are mostly absorbed or insulated by a lining of acoustic material inside the enclosure, and they partially escape from the opening that serves as a pathway for cooling air. Hence, one of the major design challenges is a choice between mutually exclusive alternatives: i.e., the reduction of the noise escaping from the opening and the securing of ventilation to establish a heat balance.

2. Ultra-low noise and iNDr

2.1 Development goals

Fig. 4 (left) shows the result of a survey on environmental noise pollution, indicating that the complaints about the noise of construction work rank second after those about factory noise.[1] As shown in Fig. 4 (right), most complaints occur in urban areas. This is because urban construction sites are small in area and a number of restrictions on the work arise from the surrounding areas. There is a need for smaller and quieter machines that work safely and show consideration for the environment of the surrounding areas.

After reviewing conventional machines, the following targets were set for improvement.



Complaints by state		
Rank	Complaints	
	Prefecture	Number
1	Tokyo	3,263
2	Osaka	1,756
3	Aichi	1,494
4	Saitama	1,122
5	Kanagawa	1,081
National total		15,849

Fig. 4 Status of environmental noise pollution

① Notable silence
Environmental protection for the surrounding area：a reduction in the power level to a figure of 5dB below the regulation value
② Reduction of machine-generated noise
Reduction of noise by 10dB in the vicinity of the cabin, at the point where the noise level reaches its maximum.

Achieving these goals would mean no more need for concern about working at night or near hospitals and would facilitate close communication among workers and ensure safety at work.

2.2 Structure of iNDr

As described previously, the enclosure opening makes the largest contribution to the total noise, so the noise from the opening must be reduced.

A system, the Integrated Noise & Dust Reduction Cooling System (iNDr), has been designed to suppress the emission of sound, while securing the flow of cooling air in an enclosure. This has improved the soundproofing performance significantly. The system has also been used to install a dust filter in the duct path, which has significantly improved the ability to clean heat exchangers such as radiators and oil coolers. Their cleaning has been a major issue for conventional construction machines. **Fig. 5** shows the structure of iNDr. **Fig. 6** compares the iNDr system with a conventional structure.

The following are the five points given consideration in designing the system.

① Apertures are closed as much as possible, such that the intake and discharge of air to and from the engine room occurs only at one opening.
② In the conventional structure, sound sources are visible straight from the opening, which limits the soundproofing effect. The newly developed structure includes an opening having the offset structure of a sound absorbent duct, which significantly reduces the radiation of sound.
③ In consideration of the noise and exhaust at the lateral sides of the machine, the opening is located on the top surface.
④ The sound-absorbing performance inside the enclosure is improved by acoustic materials.
⑤ A dust filter is placed in the duct in front of the radiator, such that the filter can be installed and removed easily.

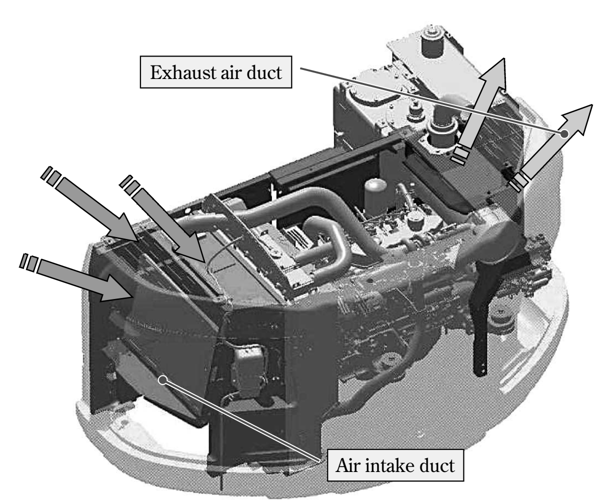


Fig. 5 iNDr structure

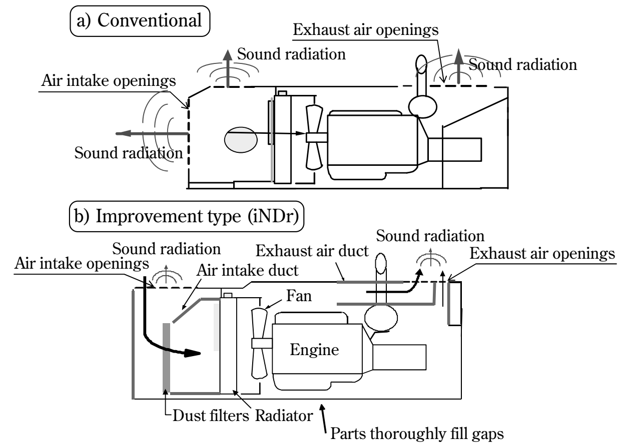


Fig. 6 Comparison of conventional type and improvement type (iNDr)

In the inlet duct, there is a trade-off between draft resistance and sound attenuation. Therefore, the off-set between the pathway positions of the opening and cooling fan was optimized by analysis and bench testing.

We have applied for 8 patents, including peripheral patents.

2.3 Analysis and experimental method

2.3.1 Experiment on soundproofing performance of engine enclosure

As previously described, one of the major challenges in the design is the choice between mutually exclusive alternatives: the reduction of the noise escaping from the opening and securing ventilation to establish a heat balance. Thus, the soundproofing structure of the enclosure must be considered. To solve such problems, experiments on actual size machines, as well as numerical simulations, are effective. An easy-to-modify mock-up apparatus was used to improve development efficiency.[2)] **Fig. 7** outlines an experimental apparatus simulating the enclosure.

The apparatus has a fan, a major sound source, which is driven by an electric motor substituting for an engine. The engine sound is emitted from an ultra-

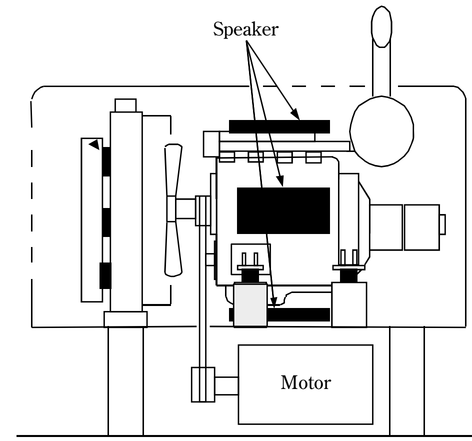


Fig. 7 Experimental apparatus of mock up model

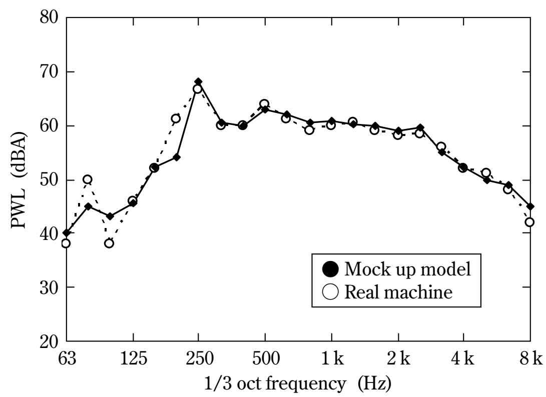


Fig. 8 Comparison of sound power between mock up and real model

thin flat speaker placed adjacent to the electric motor. The sound evaluation is based on the method set by ISO6395 for measuring exterior noise emitted from construction machinery. The evaluation includes the sound power level calculated from the noise measured at 6 points on the face of a hemisphere and the ventilation volume of the heat exchanger (e.g., radiator) measured simultaneously.

Fig. 8 compares the 1/3 octave frequency characteristics of the mock-up apparatus with that of an actual machine. As shown, the characteristics agree reasonably well, verifying the validity of the prediction.

The 1/3 octave band frequency analysis is the most commonly used method for acoustic signal analysis, in which band filters are distributed logarithmically in accordance with the frequency resolution characteristics of the human ear.

2.3.2 Estimating cooling air volume by fluid analysis

Analysis techniques have been keeping pace with the increasing speed of computers. Flow analysis, including the modeling of an entire engine room, used to take several months, but now takes about 2 weeks, making the models available for machine development. **Fig. 9** shows the result of an analysis using the lattice Boltzmann method on the cooling air flow inside an engine room. The lattice Boltzmann method approximates fluid as an aggregation of a finite, but large, number of hypothetical particles, each having a velocity. The method uses lattice Boltzmann equations to calculate the velocity distribution function from the collisions and translational motions of the particle and to determine parameters such as velocity and pressure in the flow field. So far as the speed of calculating for large-scale models is concerned, this method is superior to conventional numerical calculation based on Navier-Stokes equations and has the advantage of the calculations being made using actual shapes without simplifying them. The method is useful not only for the numerical evaluation of air flow, but also for confirming and counter-measuring the stagnant flow and eddies.

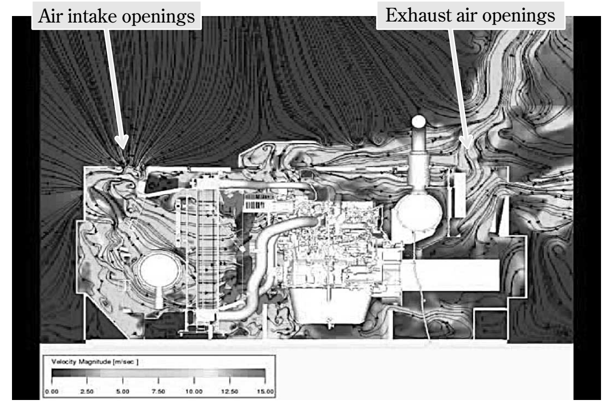


Fig. 9 Analysis of cooling air flow in engine room

2.3.3 Acoustic analysis

Conventionally, acoustic analyses required a large amount of time. Sound source models have become even more complicated. The analysis time and complicated modeling have made the practical adaptation of the analyses difficult. We have collaborated with the Mechanical Engineering Research Laboratory, Kobe Steel, Ltd., to develop a method that works in a practical way in machine development.

1) Technology of acoustic field analysis in high-frequency regions

Conventionally, the boundary element method, a type of numerical analysis technique, has commonly been used for acoustic field analyses. The boundary element method is a method for numerically solving boundary integral equations, derived from the governing differential equation for the field, through discretization. This method is advantageous in sound analysis in that it requires the meshing only of the boundary surface of the subject space and calls for no special boundary condition for the problems of open domain (e.g., acoustic emission to outdoors). However, in the case where a boundary is discretized according to the boundary element method, the boundary must be divided into pitches as short as 1/8 wavelength of the sound to attain sufficiently high analytical accuracy. Therefore, the shorter the wavelength and the higher the frequency of the sound, the finer the meshing becomes. This requires a significantly large amount of calculation time and a large memory capacity.

Fig.10 shows the relation between the number of elements and the analysis time in different analysis techniques. When considering an acoustic field analysis on the scale of construction machinery, the maximum frequency has conventionally been limited to about 500Hz. Modern computers with improved performance and a newly developed algorithm (e.g., the fast multipole boundary element method) have gradually enabled the analysis of higher frequencies; however, the requisite calculation time and memory capacity have not yet reached a level permitting the use of this method in practical design. Focusing on the fact that high-frequency sound is less affected by fluctuations, we have developed a technique for analyzing acoustic fields. The newly developed method (acoustic radiosity method) adapts the radiosity method[3), 4)] used for thermal analysis and light transmission analysis (CG rendering technique). The acoustic radiosity method also requires meshing of only the boundary surface, allowing the models to be shared with the boundary element method. Analyzing in the low-frequency range, up to about 500Hz, using the boundary element method, and analyzing in the higher-frequency range, using the acoustic radiosity method, have shortened the calculation time to 1/30 of that required by the conventional method.

2) Technology for modeling sound sources

A conventional method for acoustic field analysis requires inputting vibration velocities for all the elements of a structure. The number of elements increases with increasing frequency and reaches several tens of thousands in the high frequency region, as shown in Fig.10. Analyzing vibration velocity requires the measurements of several tens of thousands of data points, which makes the analysis impractical. We have managed to reduce the number of measurement points from several tens of thousands down to several tens by adapting an equivalent sound source method, in which the measurement points are replaced by equivalent and simple sources of sound. More specifically, the sound sources were identified by the following procedure.

① Measuring sound pressure, p, in the surrounding area during actual operation.
② Measuring the transfer function, H, of the sound pressure in the surrounding area while assuming a sound source on the surface.
③ Determining the equivalent sound source, q, satisfying the sound pressure distribution during actual operation. ($p=Hq$)

Fig.11 shows the result of accuracy verification for the acoustic field analysis up to 4,000Hz. An engine is considered, for which the vibration velocity should preferably be input at intervals of 10mm, or 1/8 of a wavelength. The result compares a case in which intervals of 200mm are applied to the conventional analysis with a case in which the same intervals are applied to the newly developed analysis involving the identification of an equivalent sound source. The newly developed equivalent sound source method, inputting a sound source at 200mm intervals, has achieved the same level of accuracy as the conventional method with 10mm intervals and has shortened the analysis and measurement time. The new technology enables the modeling of objects such as fans, whose vibration is difficult to measure directly.

2.4 Evaluation results

Fig.12 compares the sound power levels, at 1/3 octave frequencies, of the enclosures before and after the modification. In the frequency range higher than 400Hz, the noise emission of the modified enclosure

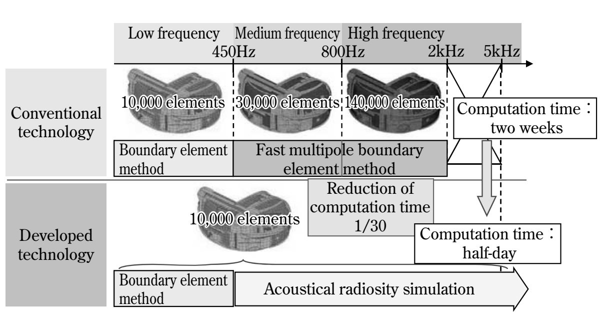


Fig.10 Sound analysis technology of high-frequency region

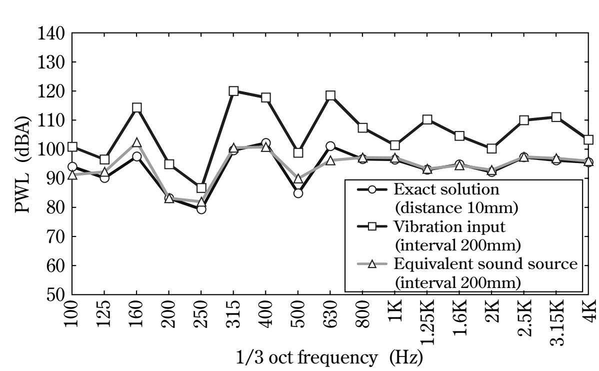


Fig.11 Modeling Accuracy of of the sound source

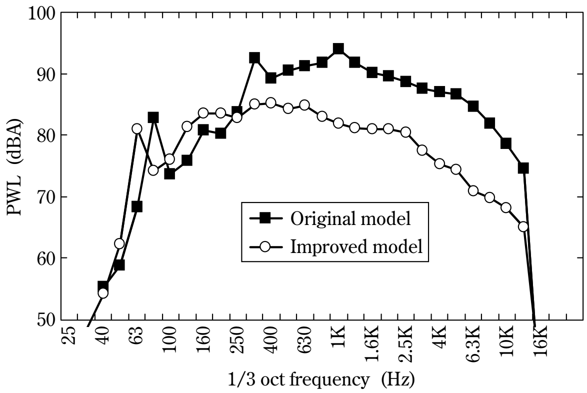


Fig.12 Comparison of measured PWL between original and improved enclosure

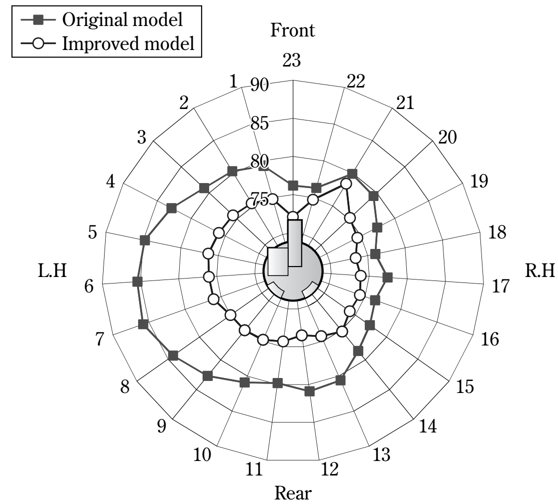


Fig.13 Comparison of noise near machine

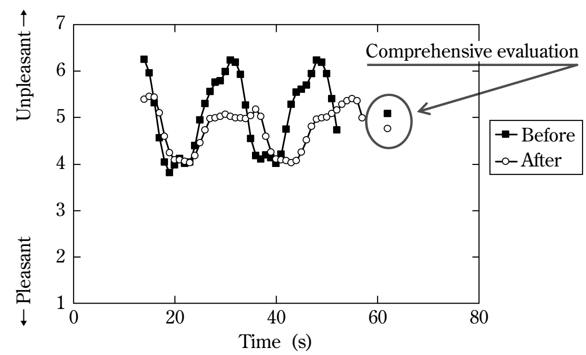


Fig.14 Result of subjective evaluation of pleasant-unpleasant

is more than 10dB lower than that of the conventional enclosure, contributing to the reduction of overall noise.

Fig.13 compares the noise levels at points one meter away from the machine. The noise is reduced by 10dB at points on the left hand side of the cabin, which allows smooth communication between the operator and workers.

Once the sound radiating from the enclosure opening is reduced significantly, the solid-borne sound of hydraulic origin, the sound emitted from vibrating surfaces, stands out more, deteriorating the sound quality. A technique for improving the sound quality has been adapted to the hydraulic pipe supports to reduce their potential for transmitting vibration. **Fig.14** shows the changes in auditory feeling[5)] over time, before and after the modification, during three cycles of excavation work. The modification has reduced the value, improving the overall result.

2.5 Product development and New Technology Information System (NETIS)

The newly developed technology is employed in three models of the ACERA Geospec SR series. As previously shown in Fig.1, the current models (depicted by △) were upgraded to new models (depicted by ○) with the aim of noise reduction. These models, SK135SR and SK235SR, have achieved a noise level that is 5dB lower than the value set by the most stringent regulation, the super-low noise standard of the Ministry of Land, Infrastructure, Transport and Tourism. The SK70SR and SK135SR have achieved noise levels as low as those of mini-excavators.

In 2010, our series was certified and registered under the New Technology Information System (NETIS) by the Ministry of Land, Infrastructure, Transport and Tourism. Thus, by exploiting our products, our clients can raise the performance rating for their construction work.

2.6 For further reduction of noise

To lower the noise level even further, the sound of the fan, the major source of noise, must be reduced. This calls for further improvement focusing on the air flow in and around the fan and the development of a cooling system with even less noise. With the recent advancements in the technology for analyzing the fluid noise of fans, a fundamental solution may be expected. It should be noted, however, that the reduction of fan noise can lead to the reduction of the constant component of mechanical sound; and when that happens, variable components linked to excavation work and hitherto masked by the fan noise, may now stand out, deteriorating the sound quality.

Conclusions

Further progress can be expected in the noise reduction of hydraulic excavators. On the other hand, the regulations on exhaust emissions are becoming more and more stringent. As a result, new challenges are emerging, including increased cooling noise due to the increased amount of heat generated by the engine and the revised equipment layout and soundproofing structure for additional exhaust purification apparatuses. More attention must be paid, not only to reducing the sound from the engine room, but also to reducing other sounds, such as the impact sounds caused by excavation attachments and the rattling sound of traveling apparatuses.

The development of new items is desired for future noise reduction. The improvement of sound quality must be based on the perceptions of those who hear the sounds. It is essential to reduce the noise level even further in the near future, not only in the surrounding area, but also inside the cabin for the amenity of the operator. In addition to the reduction of the noise level, there is a need for further improvement in sound quality, considering the fatigue experienced after extended operation of the machinery and also the fact that a certain amount of sound is required for safe operation. We will continue to pursue the goal of comfortable sound in the acoustic design of hydraulic excavators and thus contribute to provide hydraulic excavators that match the needs of society.

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