Development of Noise Reduction Technique in Small Diesel Engine

Koji Imoto*1  Toshimitsu Tsubota*1
Susumu Katayama*1  Kazuhide Ohta*1

Small Mitsubishi diesel engines are installed in construction and industrial machines. These engines must be quiet, and they must also give high performance and clean exhaust gas emission. Since machinery that is quiet gets tax advantages under the law, quietness is one of the main concerns of both manufacturers and users. To meet the new stringent noise requirements, Mitsubishi Heavy Industries, Ltd. (MHI) has developed theoretical and experimental procedures for combustion control and reduction of noise. This paper presents MHI's original conception of a combustion chamber built to reduce combustion noise. The validity of the analytical method for evaluating the vibrating and acoustic characteristics of the engine is also demonstrated.

1. Introduction

MHI is one of the most unique engine manufacturers in the world in that it manufactures a wide selection of engines ranging from 1 to 63600 PS. Of these, diesel engines of 7 to 5000 PS are manufactured at the Sagamihara Machinery Works of MHI. Engines which are smaller than 150 PS and commonly called small engines are used for agricultural tractors, combined harvesters and thresher, forklifts, hydraulic excavators as well as generators and are essential equipment in our lives. Since the close relation is given to these engines with our daily life, requirements for workability and environmental protection are very strong. In particular, in the market of agricultural machinery and construction machinery, positive efforts are continually being made to reduce noise in consideration of regional residents and the working environment of the operators using the machinery. Tax advantages are also offered for construction machinery that is quiet under the law in Japan. Thus, requirements for noise reduction of engines is very stringent.

In order to meet the stringent noise reduction requirements for these engines, MHI has comprehensively evaluated and verified both engine combustion and structure and has promoted various means of achieving lower noise.

Further, in developing small diesel engines, MHI aims at noise reduction in the engine body without relying on enclosure in terms of cost, light-weight and miniaturization, and these engines are characterized by these features. By this characteristic heat radiation of the engine to cooling water can be controlled to the minimum limit, and the vehicles can use smaller radiators. Therefore, not only cost reduction of the engine but also cost reduction and miniaturization of the vehicle body can be achieved, leading to enhanced merchandising power of the final product itself.

This paper describes the realization of low noise combustion control through the development of a combustion system using MHI's original swirl chamber shape, and the creation of a low noise structure by analysis and prediction of generation mechanism of noise.

2. Generation mechanism of noise and noise reduction procedure

Fig. 1 shows an overview of the main mechanisms responsible for the generation of engine noise. First, mechanical impact forces such as piston slap caused by impacting of the cylinder wall with the piston and bearing impact caused by impacting of the main bearings with the crank shaft due to the explosion force in the cylinder are generated. These mechanical impact forces vibrate the engine structure components such as the crank case and finally are radiated as noise from the outer surface of the engine.

Consequently, the following measures in terms of both combustion and structure are required in order to reduce engine noise.

- Control of explosion force (pressure inside cylinder) by improving combustion
- Reduction of mechanical impact forces such as piston slap and bearing impact
- Improvement of vibration transmission characteristics of crankcase, crankshaft, etc.
- Improvement of sound radiation properties of crankcase, oil pan, cover, etc.
- Reduction of mechanical sounds of timing gear, valve system, etc.

Noise reduction techniques relating to the above measures are described below in terms of both combustion and structure.

3. Noise reduction by combustion control

Low noise combustion of the pre-chamber diesel engine shown in Fig. 2 is described below. Explosion in the pre-chamber diesel engine has the following form. First, the air inside the main combustion chamber and pre-chamber is compressed and its temperature rises with the lift of the piston.

Second, fuel is injected from the injection nozzle into the pre-chamber where the air heated to a high temperature is fluidized and is ignited thereby starting premixed combustion (initial combustion). Then the combustion gas in the pre-chamber flows out into the main combustion chamber and further diffusion combustion proceeds (latter term of combustion).

In general it is known that engine noise correlates to a large extent with a maximum pressure rise in the main chamber $dP/d\theta_{max}$ (maximum value of pressure rise in main chamber for crank angle) due to explosion. Fuel injection timing retard is the easiest and the most effective method to reduce the maximum pressure rise in main chamber. However, since this
method induces a deterioration in engine performance, large retards in fuel injection timing is not allowable. It is necessary then to consider a balance between noise and performance. In addition, it is effective to use slow combustion mode by restraining the initial combustion, but when performance is considered it becomes necessary to accelerate diffusion combustion during the latter stage of combustion\cite{11}. Fig. 3 shows the cylinder pressure and its rise in case of fuel injection timing retard and in case of restrained initial combustion.

Thus, in order to reduce noise, fuel injection timing retard should be given, while, cylinder pressure rise should be reduced by restraining the initial combustion as mentioned above. However, it is then necessary to accelerate diffusion combustion in the latter term so as to secure performance. The following shows the concrete procedure for realizing the above.

3.1 Initial combustion restraint

In order to accomplish slow combustion by restraining the initial combustion it is necessary to restrain the premixture quantity of fuel and air in the pre-chamber. Therefore, the following measures are considered.

- Shortening ignition delay
- Controlling initial injection rate
- Restraining initial mixture-formation rate

By shortening the ignition delay of fuel injection to ignition, fuel injection quantity during the period of ignition delay can be restrained and premixed combustion during initial combustion can be restrained. Higher compression ratio is considered as one procedure for realizing the above. However, since the volume of the combustion chamber becomes relatively smaller with the higher compression ratio, performance deteriorates when the compression ratio is increased to over some extent.

The premixed quantity of fuel and air can be restrained by restraining the initial injection rate of fuel. In the throttle nozzle used in the pre-chamber diesel engine, the double throttle nozzle, in which the nozzle hole area is changed in two stages, is effective. Fuel injection quantity during initial injection can be restrained by this nozzle. Further, the pilot

\begin{align*}
\text{Fig. 1 Generation mechanism of engine noise} \\
\text{Respective measures for suitably addressing excitation force, vibration transmission and acoustic radiation are necessary in order to accomplish reduction in engine noise.}
\end{align*}

\begin{align*}
\text{Fig. 2 Combustion system of pre-chamber diesel engine} \\
\text{Fuel oil injected into the pre-chamber is ignited, and combustion gas flows into the main combustion chamber.}
\end{align*}

\begin{align*}
\text{Fig. 3 Changes in cylinder pressure due to combustion control} \\
\text{Sharp increases in pressure can be restrained by fuel injection timing retard and initial combustion restraint.}
\end{align*}
Fig. 4 Improvement of engine performance with new combustion system
A new combustion chamber with curved jet passage improves cylinder pressure rise ratio, specific fuel consumption and exhaust smoke.

Injection that injects fuel in two stages is one procedure.

Slow initial combustion can be realized by restraining the rate of fuel and air mixture formation during the initial injection. One of the procedures for achieving this is for the direction that the fuel is injected to be made eccentric from the center of the pre-chamber. This procedure is that the amount of air induced into the fuel spray is restrained as the fuel spray approaches the wall surface of the pre-chamber. However, this procedure cannot be executed to over some extent due to a resulting loss of engine performance. The shape of the pre-chamber jet passage also influences the initial mixture formation rate. For example, when air swirl velocity becomes lower due to the pre-chamber jet passage area being enlarged, the mixture-formation rate can be restrained. However, this procedure also induces a deterioration in performance.

As mentioned above, when the initial combustion is restrained for noise reduction, diffusion combustion during the latter term of combustion also becomes inactive and performance tends to be adversely affected. Therefore, it is necessary to accelerate diffusion combustion during the latter term of combustion as described below.

3.2 Acceleration of diffusion combustion during the latter term of combustion
To accelerate diffusion combustion in the latter term of combustion, it is necessary to accelerate mixture formation in the cylinder. Therefore, combustion gas flow characteristics from the pre-chamber to the main combustion chamber should be improved and the jet energy of the spray should be increased. However, when the pre-chamber jet passage is throttled to increase jet energy, loop loss is increased while at the same time leading to a loss in heat due to an increase in jet velocity, thereby leading to a drop in thermal efficiency.

The combustion gas flow characteristics (penetration, diffusion of jet) in the main combustion chamber are changed depending on the angle of the pre-chamber jet passage. When the angle of pre-chamber jet passage is made smaller, the jet diffusion angle in the main combustion chamber becomes smaller and jet penetration is improved.

MHI noted the influence of the angle of this pre-chamber jet passage on combustion gas flow characteristics and developed the following new combustion system[22].

3.3 New combustion system
When the angle of the pre-chamber jet passage angle is made smaller, jet penetration in the main combustion chamber is improved, but the discharge coefficient of the jet passage in the pre-chamber is decreased. On the other hand, when the angle of the pre-chamber jet passage angle is made larger, the discharge coefficient of the jet passage in the pre-chamber becomes larger, but jet penetration decreases. Consequently, a new combustion chamber has been devised. In this chamber the discharge coefficient of the jet passage in the pre-chamber is made larger and at the same time the angle of the pre-chamber jet passage angle of two stages is set to improve jet penetration. The new combustion chamber is curved so that the angle on the pre-chamber side is greater than the angle on the cylinder side.

The curved jet passage was applied to an actual engine in order to conduct comparison tests. Fig. 4 shows a comparison of the engine performance and combustion characteristics of the engine under full load. Fuel oil consumption, smoke and maximum pressure rise in the main chamber of the new combustion chamber are excellent, and the initial combustion tends to be restrained while the latter term of diffusion combustion is promoted.

In the MHI SS diesel engine the curved jet passage was introduced along with a pre-chamber shape which results in higher compression ratios. An initial mixture-formation rate intended to be restrained was adopted and further the initial injection rate was restrained through the use of double throttle nozzles. This optimization of the combustion system has led to approximately 2 to 3 dB(A) of reduction in engine noise compared with existing engines.

* Mitsubishi Heavy Industries, Ltd.
4. Noise reduction by vibration transmission control

MHI also analyzed excitation force, the vibration response characteristics of the crankcase, etc., as well as acoustic radiation properties in the course of explosion force to noise radiation in the generation mechanism of noise as shown in Fig. 1. MHI then investigated and developed noise prediction techniques and measures for noise reduction. The development period of the above can be shortened and development costs can be reduced by improving accuracy of noise prediction. Further, light-weight and cost reduction of the product itself can be realized as an added benefit.

An example of a study on noise reduction using noise prediction procedures and alteration of structure is described below.

4.1 Noise prediction procedure

The most important and difficult points in predicting engine noise are the evaluation of mechanical excitation force and precise analysis of the resulting vibrational response of the engine structure including motion part. MHI has developed a noise analysis method by which the coupled effect of a rotating crankshaft and crankcase can be taken into consideration and intends to improve the accuracy of the vibration noise analysis.

An outline of the calculation method used in this analysis is shown in Fig. 5.

First, the vibration characteristics of the respective crankshaft and crankcase are obtained through FEM analysis and testing. Second, the crankshaft and crankcase are combined, but in this case the combined stiffness is obtained from the oil film stiffness of the main bearing (considering displacement in the shaft center position resulting from rotating vibration of the crankshaft) and main bearing stiffness. In excitation force cylinder pressure, inertia force and piston slap force are taken into consideration. The force from the main bearing to the crankcase (bearing impact force) is taken into account automatically in the calculation. Vibrational response at each point in the crankcase is calculated based on the time history integration of the vibration equation which the crankshaft and crankcase coupled with the main bearings.

The normal velocity component of each FEM element is then calculated from the obtained vibrational response, and the square root average speed is obtained by square root integration over the entire surface. The power of acoustic radiation from the crankcase surface is then obtained taking into consideration proper acoustic impedance and acoustic radia-

Fig. 6 Calculated and measured engine noise spectrum
Calculated values agree well with measured values.

Fig. 7 Changes of acoustic radiation power due to structural modifications
Reductions in engine noise can be expected through improvements in rudder frame structure.
tion efficiency in the air. This acoustic radiation power is used in the evaluation of low noise structures. Sound pressure level at a distance of one meter from the engine can be obtained in consideration of the area of the observation surface.

Fig. 6 shows the calculation and measurement results obtained with this noise prediction procedure. Calculated values agree well with measured values and it was found that this prediction procedure was effective.

An example of one application of this prediction procedure is presented briefly below.

4.2 Example of study on low noise structure

The degree of stiffness required for an integral structure (rudder frame) consisting of the bearing parts and skirt parts of the crankcase was studied and suitable structure designed. The purpose is to raise the longitudinal frequency of the main bearing parts and reduce the vibrational response of the skirt parts.

Fig. 7 shows the results of this study. Noise level reductions of 1.5 dB are expected compared with existing structures.

As outlined above, MHI has been conducting noise prediction and related studies on low noise structure during the development and design stages of engines with goal of realizing lower engine noise.

5. Conclusion

The following noise reduction techniques were established through comprehensive study and evaluation from the viewpoint of both combustion and structure based on the generation mechanism of engine noise.

- Optimization of combustion chamber shape using MHI's original curved pre-chamber nozzle hole, higher compression ratio, initial combustion restraint by control of initial fuel oil consumption and combustion system promoting latter term of diffusion combustion.
- Development of precise noise analysis procedures taking into account the coupled vibration of the crankshaft and crankcase as well as evaluation procedures for low noise structures.

The following items comprise some of the future themes which will be pursued in order to realize further reductions in engine noise levels.

1) Establishment of combustion system realizing not only low noise but also low pollution (low NOx and low exhaust smoke) as well as lower fuel consumption at the same time.

2) Evaluation and verification of the optimum structure and optimum modes of combustion by establishing more precise noise prediction procedures taking into consideration engine auxiliaries.

3) Establishment of noise reduction techniques taking into consideration tone quality.

References

(1) Imoto, K. et al., Reduction of Combustion-Induced Noise in IDI Diesel Engine, Transactions of the Japan Society of Mechanical Engineers, 63-605 B (1997-1) p.329—335
