

An Advanced Method for Developing Combustion Noise through the Analysis of Diesel Combustion

Insoo Jung, Jaemin Jin, Hyunkee So, Choonggeun Nam and Kwangmin Won
Hyundai Motor Co. & KIA Motors Corp.

ABSTRACT

The source of the combustion noise of diesel engines was investigated in this paper. In the development of exhaust emission and combustion noise, we must optimize the injection parameters at the cell where engine noise can not be measured. To solve this problem, it is necessary to identify a method for developing combustion noise through in-cylinder pressure measurements. It is known that the combustion noise of a diesel engine is generated mainly in the phase of premixed combustion and depends on the rate at which the pressure increases. The combustion noise was analyzed by measuring the in-cylinder pressure and engine noise. Our results show that the combustion noise has a low correlation with the maximum rate of pressure increase. For this reason, a new index called the combustion noise index was developed based on the cylinder pressure level. This paper describes an advanced method for developing combustion noise and illustrates some examples of the results obtained.

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INTRODUCTION

To comply with increasingly strict regulations concerning exhaust emission and fuel consumption throughout the world, Green Vehicles are being progressively developed. Generally, these include clean diesel vehicles, hybrid vehicles, electronic vehicles and hydrogen fueled vehicles. From among these, clean diesel vehicles are receiving new technologies, such as high pressure injection systems, variable geometry turbochargers and exhaust after-treatment systems. Therefore, the perception of clean diesel vehicles as environmentally friendly with reduced exhaust and CO₂ emissions continues to grow. However, it is difficult to develop the combustion noise of diesel engines without deteriorating the exhaust emission because a trade-off relationship exists between them [1].

Combustion noise largely impacts the perceived sound level and sound quality of the vehicle interior noise. Therefore, it is necessary to spend significant time achieving a best balance between exhaust emission and combustion noise. Additionally, there are internal needs that must be developed for the combustion noise in the early stages of the vehicle development process. Therefore, we need an advanced method for the effective optimization of combustion noise in light of the exhaust emission. This paper is focused on the combustion excitation made by calibrating the injection parameters, such as the main injection timing,

the injection pressure, the pilot injection quantity and the pilot injection timing without changing the hardware related to the powertrain, structure paths and noise absorbing materials in the vehicle. The combustion excitation is related to the combustion noise of the diesel engine. These values were analyzed by measuring the in-cylinder pressure and engine noise. Based on the results of the analysis, a new index called the combustion noise index was developed based on the cylinder pressure level.

DIESEL ENGINE COMBUSTION PROCESS

The diesel engine combustion process can be summarized as shown in Figure 1. Liquid fuel is injected at high velocity through small orifices in the injector and is atomized into small drops and penetrates into the combustion chamber. The fuel vaporizes and mixes with the high-temperature, high-pressure cylinder air. Because the air temperature and pressure are above the fuel's ignition point, spontaneous ignition of portions of the already-mixed fuel and air occurs after an ignition delay period between the start of fuel injection into the combustion chamber and the start of combustion [2].

During the burning of fuel in the premixed combustion phase, the in-cylinder pressure increases rapidly, producing a dynamic load and high frequency oscillations from the shock



wave. The rapid change of the in-cylinder pressure is the root of combustion noise. The frequency of the structure oscillation produced by the dynamic load, which is caused by the rapid rise of the in-cylinder pressure, is equal to the natural frequency of the machine parts. The rate of pressure rise in the premixed combustion phase depends on the ignition delay and the fuel injection rate [3].

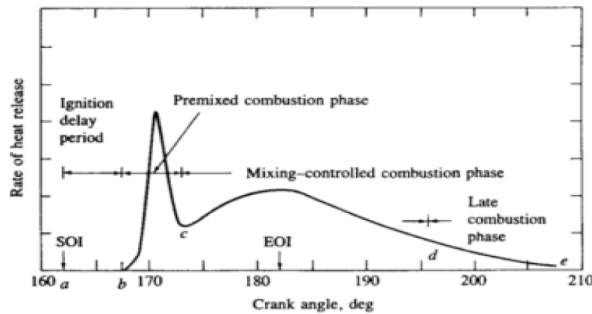


Figure 1. A typical direct injection engine heat-release-rate diagram identifying different diesel combustion process [2]

It is known that as the rate of pressure rise becomes increasingly abrupt in terms of shape, as shown in Figure 2, the combustion noise of the diesel engine rapidly deteriorates [4].

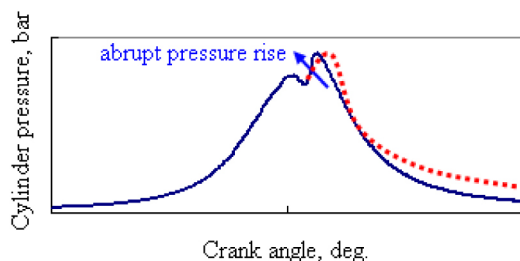


Figure 2. Cylinder pressure curve

EXPERIMENTAL EQUIPMENT

The test was performed in a semi-anechoic chamber with a EURO 5 production engine. The characteristics of the tested engine are reported in Table 1.

Table 1. The engine characteristics

Displaced volume (L)	1.7
Bore (mm)	77.2
Stroke (mm)	90
Cylinder arrangement	4 in line
Compression ratio	17.0
Fuel injection equipment	Bosch common-rail
Max. injection pressure (bar)	1600

The engine was managed by an opened electronic control unit (ECU). The ECU allowed us to control the main

injection timing, the injection pressure, the pilot injection quantity and the separation. The engine noise level is an averaged noise level measured 1 meter away from four directions (Left, Right, Front and Top) of the engine. The analysis was carried out by Artemis S/W of HEAD Acoustics. To measure the cylinder pressure of all four engine cylinders, the sensors were set with a Kistler 6056A type. The cylinder pressure was recorded in 0.5 crank angle degree (CAD) increments and averaged over 100 consecutive combustion cycles, and then analyzed by a Dewetron analyzer.

CYLINDER PRESSURE SPECTRUM

When the base calibration data for an initial car in the development process is collected, we must develop the exhaust emission and combustion noise by optimizing the injection parameters at the cell, where the engine noise can not be measured. However, at the same time, the in-cylinder pressure is always measured. Therefore, an advanced method making use of the cylinder pressure should be developed. The cylinder pressure curve can be transformed from the time range into the frequency range for correlation with the engine noise. This yields a cylinder pressure spectrum similar to that as shown in Figure 3.

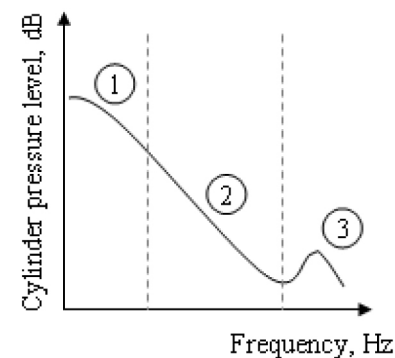


Figure 3. The cylinder pressure spectrum

It is known that the spectrum of cylinder pressure can be classified into three regions [5]. In the low-frequency region, which is plotted as the '①,' the maximum value of the cylinder pressure is mainly determined by integrating the pressure curve and the peak pressure value. The middle region of the spectrum, which is plotted as the '②' in the figure, has the distinctive feature that the pressure level decreases linearly in a logarithmic law. The slope depends on the rise rate of the cylinder pressure. The third region, plotted as the '③' in the figure, exhibits a peak in the pressure level. This peak is due to the rapid elevation of the in-cylinder pressure in the local district at the beginning of combustion, which is related to the second-order rate of pressure rise. It causes the gas in the combustion chamber to oscillate in resonance and is mainly dependent on the bowl geometry and the gas temperature [6, 7]. Because both the chamber geometry and the gas temperature change during the

combustion process, the resonance of the combustion chamber is an unsteady phenomenon [8]. Figure 4 was obtained at 1500rpm and BMEP 6bar. As can be observed in the figure, region '③,' of the tested engine occurred at the 6.3kHz third octave band.

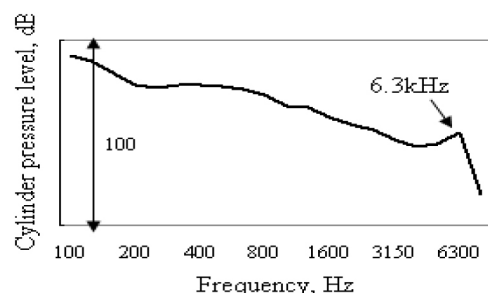


Figure 4. The cylinder pressure spectrum at 1500rpm

To find the frequency range related to region '①,' the test was carried out by changing the injection parameters as given in Table 2.

Table 2. The differences in the injection parameters in comparison to the base data

@1500rpm, BMEP 6bar

A	The main injection timing is retarded by 3 CAD.
B	The injection pressure is increased by 50bar.

@1500rpm, BMEP 4bar

C	The base data
D	The pilot injection quantity is increased by 0.6 mg.

Figure 5 shows the cylinder pressure and the cylinder pressure level (CPL) with respect to the 'A' and the 'B' at 1500rpm and BMEP 6bar. The following Figure 6 presents the results obtained under 1500rpm and BMEP 4bar for 'C' and 'D.' From Figure 5 and Figure 6, it can be determined that the differences in the maximum cylinder pressure (MCP) are 8.3bar and none, respectively. As can be seen, the frequency range of '①,' corresponds to a frequency below the 250Hz third octave band, which is distinguishable in comparison to changing the MCP.

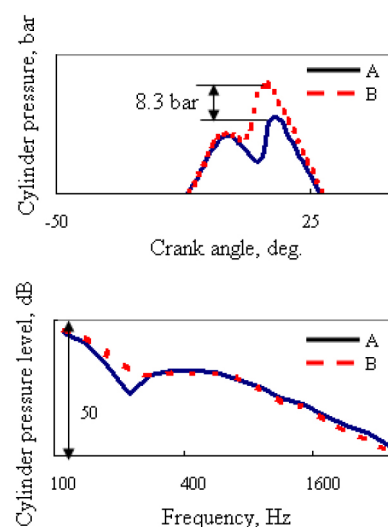


Figure 5. The results after changing the injection parameters at 1500rpm and BMEP 6bar

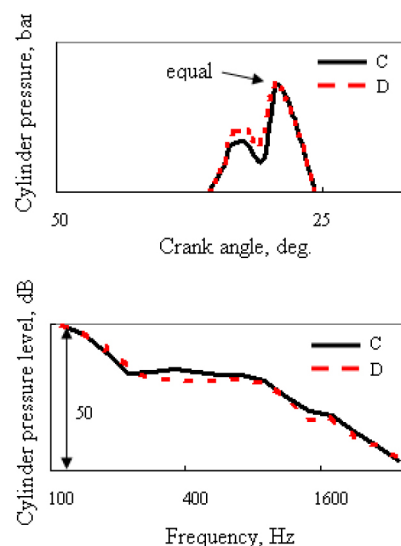


Figure 6. The results after changing the injection parameters at 1500rpm and BMEP 4bar

RELATIONSHIP BETWEEN THE MAXIMUM PRESSURE RISE RATE AND ENGINE NOISE

The engine noise and the maximum pressure rise rate (MPRR) of the cylinder pressure, when measured at an engine speed of 1500rpm with a brake mean effective pressure (BMEP) of 6bar, are shown in Figure 7. The result, i.e., that the main injection timing is retarded by 2 CAD, is plotted as line 'E'. Line 'F' represents the result in which the injection pressure is reduced by 100bar. From Figure 7, it can be seen that the engine noise of 'E' is higher than that of 'F' at frequencies over the 1kHz third octave band despite the fact that their maximum pressure rise rates are equal.