A Study on the Relation between Cylinder Pressure Process and Combustion Noise in Engines

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(Received July 15, 1976)

Abstract

This paper is concerned with the noise emitted by the surface of reciprocating internal combustion engines. At first, the relevance of characteristic values of cylinder pressure process to emitted noise was reviewed. Next, the transfer coefficient between the cylinder pressure spectrum and sound pressure spectrum of noise was estimated, and an assessment of four kinds of four-stroke engine as noise generating objects was made. Finally, by the aid of these results, an attempt was made to separate the combustion noise and the mechanical noise from the engine noise.

1. Introduction

In some studies, the mechanism of transfer and generation of the solid borne noise in engines (i.e. engine noise) and the means of noise reduction have been discussed. However, owing to the complexity, the clarification thereof is extremely difficult.

The pressure vibration caused by combustion is damped in the structure and radiates from its surface. If it were possible to determine or pinpoint the transfer function between the cylinder pressure development and the combustion noise, it would become possible to presume the combustion noise from the cylinder pressure development to some extent. Moreover, it would also become possible to estimate the contribution of the combustion noise to the total noise even in cases where the combustion noise is masked by the mechanical noise at high speed running.

Thus, in this study, an attempt was made to separate the combustion noise and the mechanical noise from the engine noise by estimating the transfer coefficient between the cylinder pressure and the engine noise, and satisfactory results were obtained as follows.

2. Experimental apparatus and procedures

Four kinds of single cylinder, four-stroke engine were tested. Three of them were water cooled diesel engines, and another one was air cooled gasoline engine. The main specifications are shown in Table 1. In each engine, a strain gauge type pressure transducer (Kyowa PHF-10T, PE-5KP) was attached to the main chamber for measuring the cylinder pressure process. The output from this transducer was amplified by an I. C operational amplifier and recorded by a synchroscope simultaneously. At

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Table 1. Specifications of test engines.

Test Engine	Engine A	Engine B	Engine C	Engine D
Model	Mitsubishi DV-4 (Diesel)	Kubota LC-1 (Diesel)	Yamma TR-15 (Diesel)	Mitsubishi G3L (Gasoline)
Type of combustion chamber	Pre-chamber	Direct injection (BIP)	Swirl chamber	Side valve
Bone × Stroke mm	95×110	110×150	95×106	65×52.5
Compression Ratio	19.0	17.4	19.5	5.9
Rated Output PS/rpm	18.2/3200	10.0/1200	15.0/2600	3.0/3600

the same time the crank angle and needle lift of the injector were detected by using a phototransistor.

The engine noise was measured by a condenser microphone (B & K 4133), a frequency analyzer (B & K 2107, LION SA-21, SA-10) and a level recorder (B & K 2305). A piston-phone and a function generator were used for the calibration of noise and cylinder pressure level.

The test was mainly carried on engine A for convenience.

3. Relation between the characteristic values of cylinder pressure process and engine noise

It was noted that the engine noise was remarkably affected by the combustion process. It is generally accepted that the level of engine noise is affected by the maximum pressure of combustion in low-frequency range and the rate of pressure rise has a remarkable influence on the high-frequency portion of engine noise. These assumptions are supported by the relation between the engine noise and the cylinder pressure process.

In view of the above, the influences of combustion on the engine noise were investigated. Fig. 1 shows experimental results of the rate of heat release, cylinder pressure process and sound pressure level versus three kinds of fuel, i.e. gas oil (specific gravity 0.83, cetane number 55), undoped gasoline (0.74, 35) and regular gasoline (0.75, 14). In this figure, the maximum value of rate of heat release and rate of pressure rise grow with decreased cetane number of fuel. Rapid combustion raises the sound pressure level of engine noise in the frequency range of 500∼3,000 Hz.

Formerly, the maximum pressure $p_{\max}$, the pressure rise Δp and the rate of pressure rise $dp/d\theta$ have been used as the characteristic values of cylinder pressure process. Fig. 2 shows the coefficient of correlation between the sound pressure level of noise and the characteristic values in each frequency range. The sound pressure level correlate with these values, especially $dp/d\theta$, to some extent in the range of 300∼4,000 Hz. None of these, however, has given a close correlation with emitted noise and it is rather unlikely that only one quantity can represent the complex form of the cylinder pressure process.

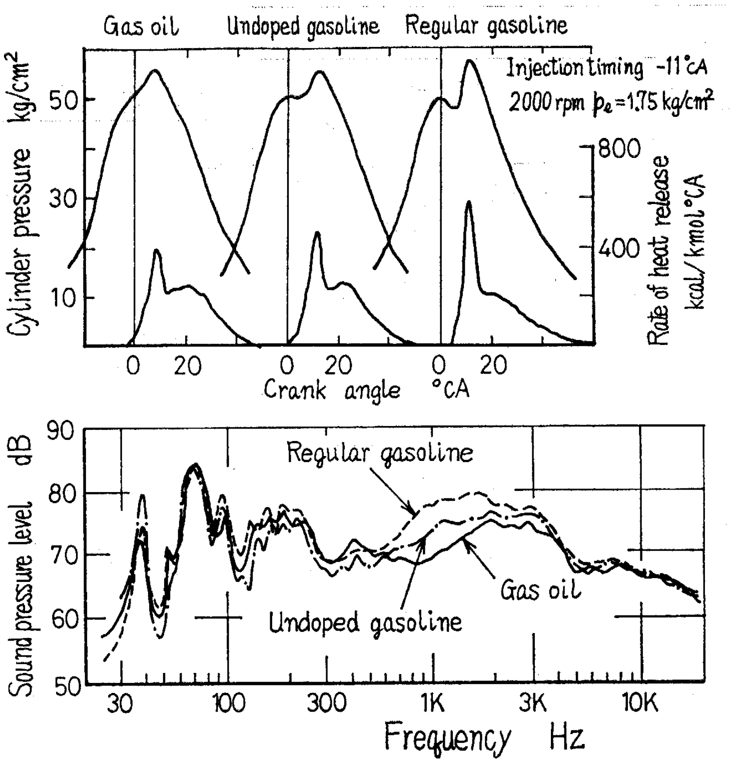

Fig. 1 Comparison of cylinder pressure process and engine noise spectra.

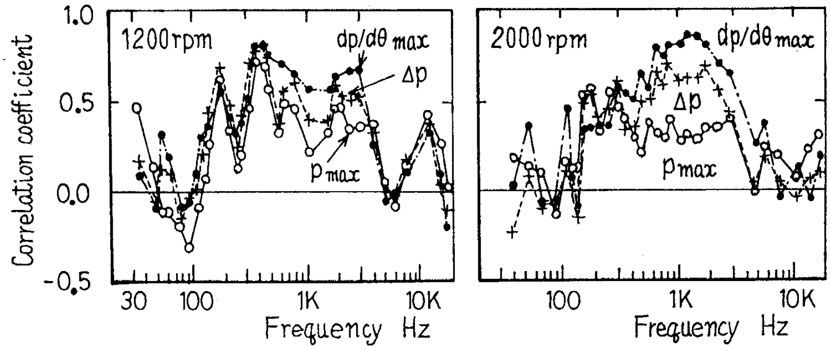

Fig. 2 Correlation coefficient between characteristic values of cylinder pressure process and engine noise.

4. Frequency characteristics of noise generation and transmission

4.1 Relation between cylinder pressure level and sound pressure level

It is extremely difficult to clarify the transfer mechanism of engine noise because the engine is constructed of numerous complex components containing parts which are discontinuous. But it is noticed that the impulsive forces affecting the piston, cylinder liner and cylinder head are intensified by abrupt combustion so that the emitted noise such as the piston slap noise increases in a certain frequency range. This trend seems to depend on the frequency characteristics of engine construction.

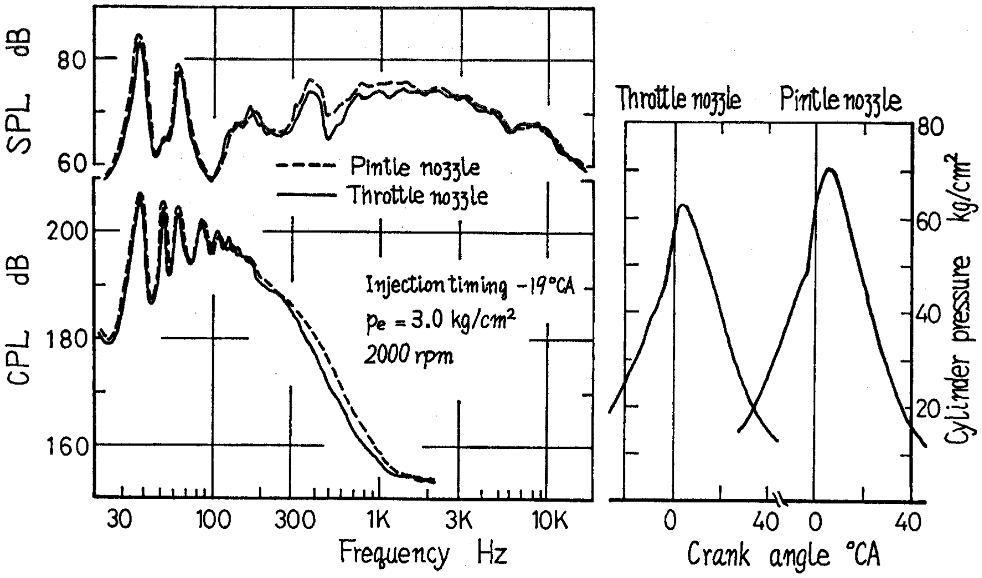

Fig. 3 Cylinder pressure level CPL and sound pressure level SPL of engine noise.

The frequency characteristics of waveform, such as cylinder pressure development can be obtained by frequency analysis. Fig. 3 shows the cylinder pressure development, the cylinder pressure level (CPL, re. 2×10^{-5} Pa) and the sound pressure level (SPL, re. 2×10^{-5} Pa) of engine noise. The relationship between CPL and SPL has been reported by T. Priede and co-workers1)~3) and confirmed by the authors in the previous paper4),5).

To sum up these results, the engine noise consists of noise related to the engine speed and that related to the cylinder pressure level. The former can be defined as the mechanical noise and the latter as the combustion noise caused by cylinder pressure.

4.2 Calculation of transfer coefficient

As described above, the engine noise can be considered as the sum of combustion noise and mechanical noise. Thus, calculation of transfer coefficient and separation of the engine noise into combustion noise and mechanical noise were attempted under the assumption that the mechanisms of vibration transfer and noise generation are not affected by the cylinder pressure process, hence the sound pressure varies in proportion to cylinder pressure at each frequency range since the mechanical noise corresponds to constant engine revolution.

Based on the above assumption, formula can be obtained for each frequency as follows.

$$(SP_e)=(TRC_1)\times(CP)+(SP_{m1})$$

where

SP_e : sound pressure of engine noise
TRC_1: transfer coefficient
CP : cylinder pressure

SP_{m1} : sound pressure of mechanical noise

SP_e and CP obtained as SPL of the engine noise and CPL in dB are converted to pressure level.

Through estimation of SP_e and CP under different combustion processes and determination of the formula described above in each case, the transfer coefficient TRC_1 and SP_{m1} may be obtained by solving these simultaneous equations. Fig. 4 and Fig. 5 show the sound pressure level of SP_{m1} (SPL_{m1}) and the transfer coefficient obtained in this manner for each engine speed (test engine A). Here, the standard deviation σ was $3.0 \sim 10.0$ dB for SPL_{m1} and $0.2 \sim 0.5$ for the transfer coefficient.

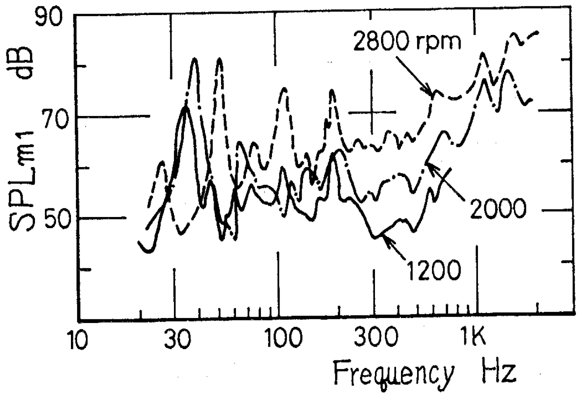

Fig. 4 Influence of engine speed on SPL_{m1} (engine A).

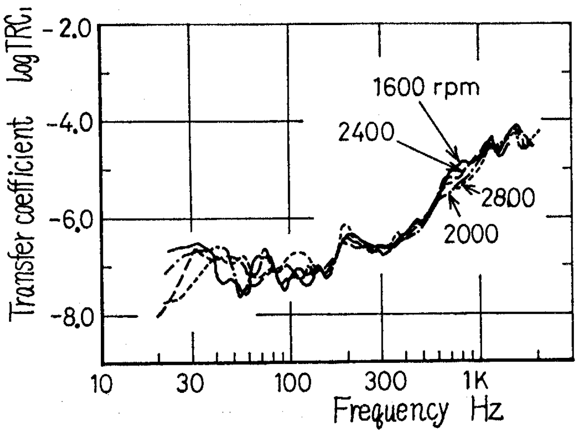

Fig. 5 Frequency characteristics of noise generation and transmission (engine A).

The SPL_{m1} evidently increases with the engine speed as illustrated by the calculated results shown in Fig. 4. It is obvious that a rise of SPL_{m1} with an increase of the engine speed is caused by an increased impulsive force.

In this paper, our previous discussion progressed with the assumption that the SPL_{m1} and the transfer coefficient remained constant in each engine speed. Consequently, the SPL_{m1} increased rapidly with rise in the engine speed as discussed above. Thus, if it were confirmed that the transfer coefficient shows the same value in each frequency range under varied speeds, the transfer coefficient would seem to indicate the frequency characteristics in noise generation of the tested engine. In Fig. 5, only slight differences of TRC_1 at each speed were observed except in a few parts of low-frequency range. As a result, the frequency characteristics in the noise generation of test engine A may be obtained successfully.

For the spectra of engine noise and cylinder pressure obtained by the third-octave band frequency analyses, the formula can be expressed for each frequency band as follows.

$$(SP_e)^2 = (TRC_2) \times (CP)^2 + (SP_{m2})^2$$

Fig. 6 shows SPL_{m2} and the transfer coefficient TRC_2 at each engine speed (test engine D). As is evident from the figure, the relationship between sound pressure of

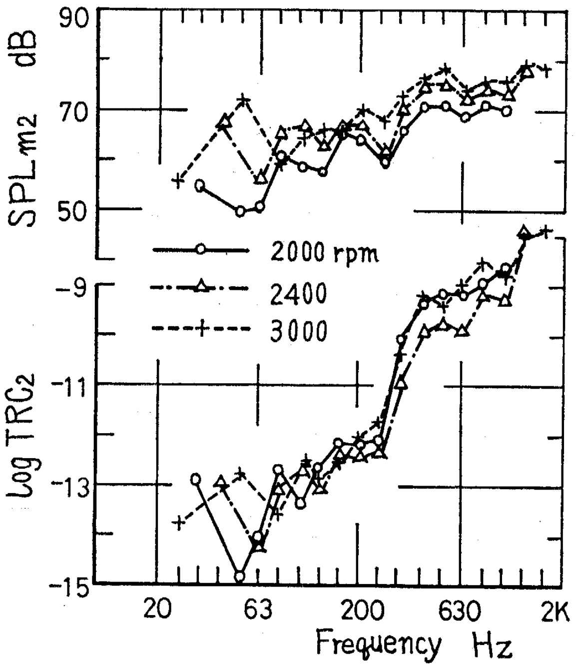

Fig. 6 SPL_{m2} and TRC_2 of engine D (third-octave band level).

emitted noise and cylinder pressure is also maintained in each frequency band.

5. An example of assessment to the engine noise generation

Fig. 7 shows CPL and SPL of the engine noise of three kinds of diesel engines (test engine A, B and C) under controlled operating conditions, same for the three engines as far as possible. As shown in this figure, little difference of CPL was observed. On the other hand, considerable disparity in SPL was obtained among three engines. TRC and SPL_{m1} are compared in Fig. 8. Collectively, TRC_2 of engine D was shown as $\log\sqrt{TRC_2}$ in comparison with TRC_1.

As may be seen in this figure, SPL_{m1} and TRC_1 of engine A are less than those of the other engines. But in contrast, TRC_1 of engine B is higher in the frequency range above 200 Hz and of engine D is also higher above 300 Hz. Hence, in the case of engine B, intensifying of damping of combustion impact through the engine structure will be effective as a way of noise reduction. Also, by the reduction of a prominent peak of SPL_{m1} near 200 Hz, a sharp reduction of noise level may be expected.

6. Isolation of mechanical noise and combustion noise

Engine noise (SPL_e) is divided into various types of noise, such as combustion noise (SPL_c) and mechanical noise (SPL_m). Then combustion noise (SPL_c) is divided into two kinds of noise, one of it depends on compression and the other comes from combustion. If the difference between the noise caused by cylinder pressure ($TRC \times CP$) and that caused by compression pressure ($TRC \times CP_{comp}$) is defined as the net

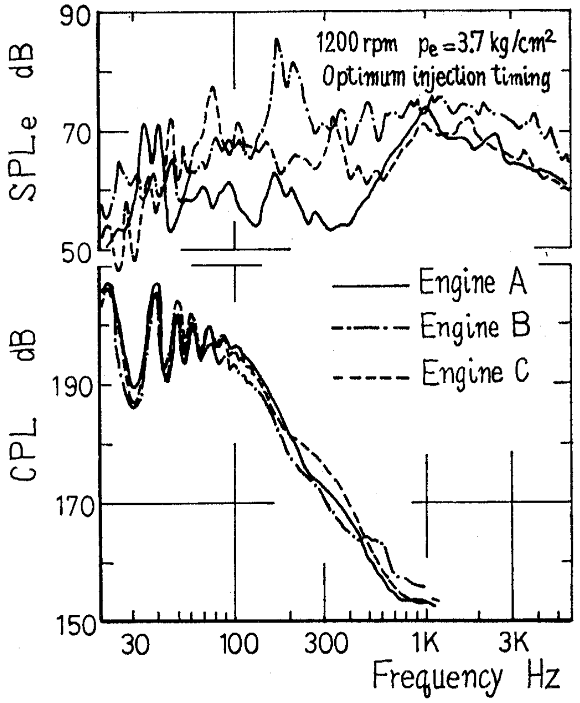

Fig. 7 Comparison of CPL and SPL_e.

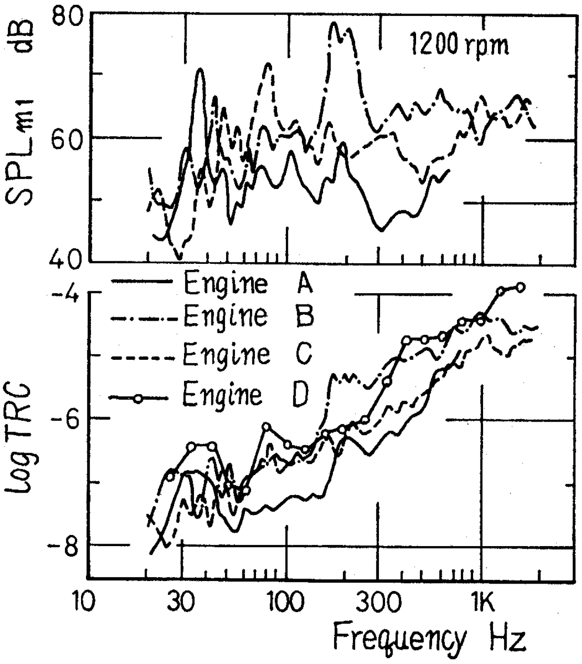

Fig. 8 Comparison of TRC and SPL_{m1}.

combustion noise (SPL_{comb}), this shows that the noise purely results from combustion. Moreover, CPL of the compression engine rarely exceeds that of a running engine in a narrow frequency range. In this case, the noise caused by cylinder pressure is treated as a compression noise.

In engine A, SPL_m, SPL_{comp} and SPL_{comb} were obtained enabling an estimation of ratios of these noises. Fig. 9 shows an example of the various kinds of noises separated from the running engine noise. As shown in this figure, SPL_m accounts

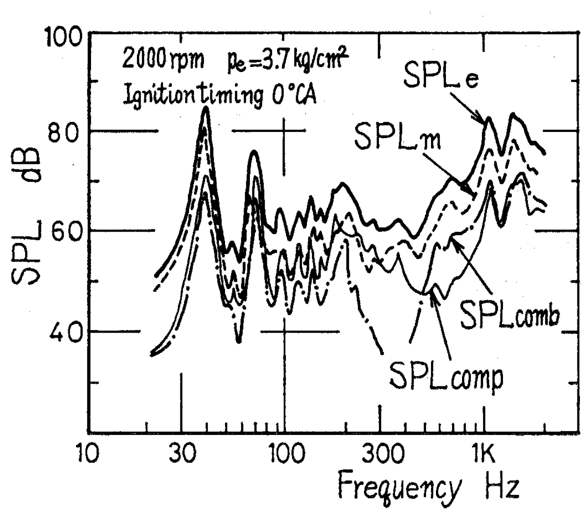

Fig. 9 An example of separation of engine noise (engine A).

for a large part of engine noise. The compression noise exceeds the net combustion noise particularly in the region of $400 \sim 500$ Hz and is less in $500 \sim 1{,}500$ Hz. Thus, the net combustion noise SPL_{comb} should be taken into consideration when discussing the combustion noise because of its dependence on combustion development.

7. Conclusion

A summary of the results is given below.

(1) The engine noise correlate with $dp/d\theta$ in a certain frequency range to some extent, but it is difficult to represent the complex form of the cylinder pressure development by only one quantity.

(2) An attempt was made to separate SPL_{comb}, SPL_{comp} and the SPL_m from the engine noise by estimating the transfer coefficient between the cylinder pressure spectrum and sound pressure spectrum of noise. And satisfactory results were obtained.

(3) The transfer coefficient was not influenced by the engine speed. Thus, it seems to represent the frequency characteristics of noise generation and transmission of an engine.

(4) An assessment of engines regarding the noise source was carried out successfully using the proposed methods.

The authors are deeply grateful to Dr. Tadashi Murayama, Professor of Hokkaido University, and Mr. Haruo Izumi and the internal combustion engine research group of Yamaguchi University. This research was partly subsidized by the Committee of Engine Noise Reduction of the Japan Society of Mechanical Engineers (Chairman; Dr. Motokazu Fukuda) and scientific research fund from the Ministry of Education.

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