Analysis of Combustion Induced Noise of Engine by Single Explosion Excitation
(2nd Report: Application of Transmission-radiation Coefficient to Running Engine)

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Combustion impact is one of the most predominant sources of engine noise. The transmission-radiation coefficients of combustion noise, which were defined as a conversion power ratio from the combustion impact to the emitted noise, were studied with both a stationary engine excited by a single explosion and an operating engine. The characteristics of these coefficients obtained in the same engine coincided with each other, so it can be said that the transmission and radiation of combustion noise of an operating engine are analogous with those of a stationary engine, to a certain extent. Then, the vibration response for combustion impact and the noise radiation coefficients were examined for each engine wall to identify their contribution to the total combustion noise.

Key Words: Internal Combustion Engine, Sound, Combustion Impact Noise, Single Explosion Excitation, Transmission-radiation Coefficient

1. Introduction

In the previous paper[1] the relationship between the power affecting the inner wall of the combustion chamber and the power of combustion-induced engine noise was studied with a single explosion excitation. A method was also proposed to clarify the transmission-radiation characteristics of combustion-induced noise through individual paths with the aid of vibrational and acoustical isolation. This paper describes the transmission-radiation coefficient (TRC) of combustion-induced engine noise comparing single explosion excitation and the firing operation of an engine.

Priede et al.[2] and the authors[3] proposed "attenuation" and "transfer coefficient" respectively as the measures of the noisiness of the operating engine structure. These show, however, the relation between the cylinder pressure process and the sound pressure measured at a point apart from the engine. Therefore, it is difficult to evaluate the influences of the engine size and the vibrational and acoustical characteristics on these quantities.

In this paper, the TRC is introduced as the power ratio of combustion-induced engine noise to the cylinder pressure. TRCs obtained by different excitation methods were compared to clarify the generation mechanisms of the combustion-induced noise of an operating engine. The evaluation of noisiness was also made by calculating TRCs for three different types of engines. The vibration transmission coefficient and the noise radiation coefficient were separately investigated as two parts of the TRC of an engine structure.

2. Experimental Apparatus and Procedures

The main specifications of the three types of test engines are shown in Table 1. Each test engine was set in an anechoic room. A baffle was set up around the engine to insulate the noise radiated outside the measuring surfaces, and to make it possible to measure the noise in a hemi-free field.

In the single explosion excitation test, the flywheel was fixed by a stopper to prevent crankshaft rotation. Piston position was set at combustion T.D.C. where the combustion impact mostly occurs in engine operation. In order to generate the single explosion, LPG, pure oxygen and air were charged one after another, then the mixture in the combustion chamber was ignited with a spark plug. A schematic of the setup is shown in Fig.1. Each gas was supplied through pressure control valves, and the mixing ratio was set at 1:7:3 in volume. Si-bond was used to fill up the piston-liner clearance to keep the airtightness of the combustion chamber. The intake and exhaust pipes, a dynamometer and the supporting structures of an engine were lagged to insulate the noise radiated from their surfaces.

The cylinder pressure processes were

<table>
<thead>
<tr>
<th>Description</th>
<th>Engine I</th>
<th>Engine II</th>
<th>Engine III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder number</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bore x Stroke</td>
<td>102 x 106 mm</td>
<td>72 x 63 mm</td>
<td>56 x 50 mm</td>
</tr>
<tr>
<td>Total displacement</td>
<td>864 cc</td>
<td>256 cc</td>
<td>123 cc</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>19.5</td>
<td>5.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Maximum power</td>
<td>1310W/2400rpm</td>
<td>5.10W/2000rpm</td>
<td>9.50W/7000rpm</td>
</tr>
<tr>
<td>Fuel</td>
<td>Gas oil</td>
<td>Gasoline</td>
<td>Gasoline</td>
</tr>
</tbody>
</table>
detected by a strain gauge type or a piezo type pressure transducer mounted flush to the cylinder head wall of each test engine. A shaker (B&K 4809) and an impulse hammer (PCB 291A) were employed to measure the vibration response on each portion of the engine structure. The main instruments for measuring noise and vibration were the same as we described in the previous report.

The frequency characteristic for each vibration and noise response generated in one cycle of an operating engine was examined with the aid of the partial frequency analysis method.

3. Transmission-radiation Characteristics of Combustion Induced Noise

3.1 Transmission-radiation coefficient

Figure 2 shows the time histories of the cylinder pressure, the vibration acceleration response on each portion of the structure and the generated noise comparing single explosion excitation with firing operation of engine (engine 1). The rates of pressure rise for each excitation are 4.3 and 3.9 MPa/ms (dp/dθ=0.83MPa/°CA), and they are regarded as roughly the same value.

Large and sharp responses are seen in the engine vibration not only with single explosion excitation but also with firing operation. From the results shown in Fig.2(b), the main origin of the noise in engine 1 seems to be the combustion induced noise which is important in understanding the transformation mechanism of combustion impact and in considering the reduction of vibration and noise in the engine.

Figure 3 shows the relationship between the cylinder pressure level Lcp (re. 20μPa) and the sound pressure level of combustion impact noise Lbp (re. 20μPa) for some 1/3 octave band frequency components obtained in the single explosion excitation. The experimental values are distributed along the 45° gradient line. As can be seen in this figure, the relation between combustion

![Diagram of schematic arrangement of single explosion excitation rig](image)

![Graph of sound pressure level vs. cylinder pressure level](image)

![Time histories of cylinder pressure, vibration acceleration and radiated noise](image)
impact and radiated noise seems to be roughly linear even in as complex a structure as an engine.

In the previous paper, the transmission radiation coefficient $G$ was defined as the conversion ratio of the power affecting the inner wall of the combustion chamber $W_c$ to the sound power generated from the outer surfaces $W_b$ in a stationary engine. The level of $G$ can be obtained with the aid of the cylinder pressure level $l_{cp}$, the area of combustion chamber wall $A_c$, and the power average of the sound pressure level of combustion noise $l_{bp}$ calculated on an assumed surface with an area of $A_b$, that is

$$10\log G = l_{bp} - l_{cp} + 10\log\frac{A_c}{A_b} \quad \cdots \cdots \cdots \cdots \cdots (1)$$

For an operating engine, the authors proposed "transfer coefficient" between the cylinder pressure and the sound pressure of combustion induced noise. This coefficient can be modified in terms of power in each band frequency component, that is

$$W_s = C \times W_m + W_n \quad \cdots \cdots \cdots (2)$$

where $W_s$ is the power of engine noise, $W_m$ is the noise power generated by engine revolution mechanical noise, and $W_n$ is the noise power generated by combustion induced noise. Most of $W_s$ is the noise power generated by combustion induced noise, and therefore, $W_m$ seems to be constant under the same engine speed.

Through estimation of $W_s$ and $W_c$ in different combustion processes with same engine speed and determination of the formula (2) in each case, the TRC can be obtained by solving these simultaneous equations. In the estimation of $W_c$, the area of combustion chamber wall $A_c$ was the one employed at T.D.C.

3.2 Comparison of TRCs between single explosion excitation and firing operation

Figure 4 compares the TRCs of the combustion impact noise obtained by the single explosion excitation and by firing operation in the same engine. A good agreement between the values of $G$ obtained in the single explosion excitation and in the firing operation is seen in engine I as shown in Fig.4(a).

Figure 4(b) shows the same comparison of the $G$s on engine II. The difference in $G$s is rather large in comparison with engine I. This difference in $G$s is strongly related to the fact that some impulsive responses having the same level as the combustion impact response happened in the same cycle of the operating engine I. Then, the partial frequency analysis method (9) was applied to the responses caused by combustion impact. As shown in Fig.4(b), the difference in $G$s obtained for both excitations was decreased by the application of this method.

From these results, it can be seen that the single explosion excitation is one of the most practical ways to estimate the transmission radiation characteristics of the combustion impact noise of engine structure especially in the high frequency range where the SN ratio is small in the operating engine.

3.3 TRCs for various engines

Figure 5 shows the TRC obtained by single explosion excitation for three types of engines listed in Table I. In this figure, it is seen that the TRCs become large, i.e. the combustion impact power is easily transferred to the noise power in high frequency range. This tendency is clearly recognized with engines II and III.

This tendency comes from the fact that both engines are air-cooled type. In an air-cooled engine, cooling fins are fitted to the outer surfaces of the cylinder head and block. Besides, the cylinder block is directly excited by pressure vibration and the piston. These conditions help interdependently transform combustion impact to engine

Fig. 4 Comparison of TRCs obtained in single explosion excitation and in firing operation

Fig. 5 Comparison of TRCs between three test engines
noise. In the low frequency range, the TRC of the engine I is high in comparison with the values for other test engines. The cause seems to lie in the fact that the size of engine I is relatively large, therefore, the outer surfaces of this engine radiate the low frequency noise comparatively easily. The distinctive character of TRC in each engine is that the TRC has peaks around 400Hz, 1.0kHz and 2.0kHz in engine I, around 1.6kHz and 4.0kHz in engine II and around 500Hz and 2.5kHz in engine III.

Combustion impact transmission paths can be classified into three types:  
1. Gas excitation path  
2. Piston-cylinder path  
3. Piston-crankshaft path

The effects of noise transmitted through the piston-cylinder path on the total combustion impact noise are shown in Fig.6. In this experiment, the original and modified pistons (replacing the piston rings with rubber O-rings) were used.

Engine I, there is no difference in the TRC between either structure. This leads to the conclusion that the effect of noise through the piston-cylinder path is negligible against the noise passing through the other transmission paths. While, in engine II, the combustion impact power is significantly transmitted through this path in the frequency ranges below 250Hz and above 1.6kHz.

The TRC was investigated as two separate elements to clarify the mechanism of combustion impact noise. One element was the vibration transmission coefficient which expressed the characteristic of transformation from combustion impact to vibrational response on the outer surfaces of the engine structure, the other was the noise radiation coefficient which showed the transformation from vibrational response to radiated noise.

4. Vibration Transmission Characteristic

4.1 Vibration transmission through engine structure

The vibrational response which originated in the single explosion excitation was examined in each transmission path by the acceleration pickup attached to points of engine I's structure as shown in Fig.7.

The vibration transmission characteristic in the cylinder-axis-direction of the piston-crankshaft path is shown in Fig.8 in terms of the difference between the vibration acceleration level Lv (re. 10μm/s²) and the cylinder pressure level Lcp. The frequency characteristics of vibration transmission in this direction show a high level in the range of 500-7kHz, particularly around 2.5kHz at each measuring point. This means that the attenuation of the combustion impact energy in this frequency range is relatively small in comparison with that in the other frequency ranges.

When the piston is advanced to the position of 15°CA B.T.D.C., the value of Lv-Lcp decreases in the high frequency range above 2kHz on the lower surface of the piston top and in the ranges below 250Hz and above 1.0kHz at the small end of the engine.
connecting rod. The cause may be because
the cylinder axial component of combustion
impact energy passing through the piston-
crankshaft path decreases with an increase
of the crank angle, while the radial
component increases. There is no significant
change in the vibrational response at the big
end of the connecting rod and in the
balancing weight with an increase of the
 crank angle. Overall, it can be said that
the vibration transmission characteristics
of the piston-crankshaft path are not
influenced by a small change of crank angle
up to 15°CA.

Figure 9 shows the frequency character-
istics of the vibration transmission of the
piston-cylinder path. The difference between
Lw and Lcp is small at the liner supporter ③
with the change of crank angle, while it is
large at the piston skirt ② and the cylinder
liner ⑦. There are two cases to be con-
dered in verifying this phenomenon. One is
the case in which the cylinder liner vibra-
tion is hardly transmitted to the cylinder
block through its supporting structure with
rubber O-rings. The other is the case when
the effect of combustion impact through the
piston-cylinder path on engine vibration is
equal to or relatively smaller than that
through the other two paths.

To investigate the former case, the
piston of the engine structure with a
crankshaft isolated from the main bearings
was excited by a shaker. As shown in Fig.10,
the cylinder liner and the liner supporter
vibrate at almost the same level in the
frequency range below 3.0kHz, then it seems
that the liner supporting structure of engine I
easily transmits the vibration caused by combustion impact.

In the latter case the original piston
and the rubber O-ring piston were excited by
a shaker with white noise. Figure 11 shows
the results of this experiment in terms of
inertance. In this figure, a large
difference of inertance is seen at both
points of the cylinder liner ⑦ and the liner
supporter ③ in the range above 2.0kHz. In
the high frequency range, therefore, it can
be said that the piston-cylinder path easily
transmits the combustion impact energy and
also vibrates the liner supporter more
easily than the piston-crankshaft path does.

These results of vibration transmission
and the results of TRCs shown in Fig.6.6, lead
to the conclusion that the effects of the
gas excitation path on the combustion impact
noise in engine I are the strongest of all
the three paths in the high frequency range.

4.2 Vibration transmission coefficient of
engine surface
For the investigation of the vibration
transmission characteristics from combustion
impact to engine surface vibration, it was
assumed that the outer surface of the engine
consists of 40 vibrating plates. The vibration
responses were detected at 250
points in total, 5 points for each plate at
least. The results for each plate are shown
collectively as the eight parts illustrated
in Fig.7.

Supposing that the volume velocity of
the vibrating surface is transformed into
the acoustic power without losses Wv, we have

\[
\text{Fig. 10 Vibration response through frequency sweep experiment (shaker excitation)}
\]

\[
\text{Fig. 11 Effects of piston-cylinder path on vibration transmission characteristics (shaker excitation)}
\]
where, $<\dot{V}>$ and $<\dot{S}>$ are the temporal and spatial squared averages of vibration velocity and acceleration of the surface, $R_c$ is the characteristic resistance of the medium, $S$ is the area of the vibrating surface and $f$ is the frequency.

Accordingly the vibration transmission coefficient $G_v$, defined as the ratio of the acoustic power transformed from the surface vibration without losses $W_v$ to the combustion impact power affecting the chamber wall $W_b$, is given by

$$10 \log G_v = 10 \log \frac{W_v}{W_b} = 10 \log \frac{S}{A} - \frac{20 \log f + 10 \log \omega_{cmf}}{f^2 W_s} + \frac{L_v-L_{cmf}}{A} + 10 \log \frac{S}{A} - 20 \log f + 30 - (4)$$

where, $L_v-L_{cmf}$ is the power average of level difference between vibration acceleration and cylinder pressure, $\alpha_0$ and $W_0$ are the reference values of the vibration acceleration level and the acoustic power level respectively ($\alpha_0=10\mu$m/s$^2$, Wreyl ph).

![Fig. 12](image)

**Fig. 12** Vibration transmission characteristics of each part of engine I

![Fig. 13](image)

**Fig. 13** Contribution of each part to total engine noise

Figure 12 shows the vibration transmission coefficient for each part of engine I obtained by Eq. (4). For this engine, $G_v$ shows a large value in the range of 800-2.5kHz, and has a peak at 1.0kHz. This means that the combustion impact vibrates the engine structure and radiates the noise easily in this frequency range. To know what is the main source of combustion noise, the contribution of $W_v$ for each part of the engine to the total surface is calculated, and the result is shown in Fig. 13. The area and the ratio of each part of the engine surface are also shown in Table 2 for reference.

As shown in Fig. 13, the contribution of the body is high in the frequency range below 630Hz, that of the gear case cover is in the range of 630-2.5kHz, and especially at 2.6kHz. The contributions of the cylinder upper cover and the cylinder rear cover also show peaks in the 1.0kHz and 1.6kHz range respectively, therefore, a small part of the engine surface which accounts for only a small percentage can be the main noise source in a particular frequency range.

From these results and those shown in Fig. 12, we can conclude that the main sources of combustion noise in engine I are the gear cover, the cylinder upper cover and the cylinder rear cover.

5. Noise Radiation Characteristic

For a detailed investigation of the transmission radiation characteristic of combustion impact noise, an attempt was made to clarify the relationship between the engine surface vibration and radiated noise.

The noise radiation coefficient of a vibrating wall $\sigma$ is defined as a ratio of the combustion impact noise power radiated from wall $W_b$ to $W_v$. Consequently, the coefficient $\sigma$ can be expressed by $G$ and $G_v$ for the single explosion excitation, as

$$10 \log \sigma = 10 \log \frac{W_b}{W_v} = 10 \log G - 10 \log G_v$$

In the case of firing operation, the coefficient $\sigma$ is calculated through direct measurement of $W_v$ and $W_b$.

Figure 14 shows the experimental results of the noise radiation coefficient for the outer surfaces of engine I's structure. Figure 14(a) shows the frequency characteristics of $\sigma$ for the gear case.

Table 2 Area ratio of each wall to total engine surface

<table>
<thead>
<tr>
<th>Surface</th>
<th>Area (m²)</th>
<th>Area ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder head</td>
<td>0.0558</td>
<td>7.8</td>
</tr>
<tr>
<td>Gear case cover</td>
<td>0.1260</td>
<td>17.4</td>
</tr>
<tr>
<td>Cylinder block cover</td>
<td>0.0371</td>
<td>5.2</td>
</tr>
<tr>
<td>Cylinder upper cover</td>
<td>0.0242</td>
<td>3.4</td>
</tr>
<tr>
<td>Cylinder rear cover</td>
<td>0.0420</td>
<td>5.9</td>
</tr>
<tr>
<td>Oil pan</td>
<td>0.0769</td>
<td>10.8</td>
</tr>
<tr>
<td>Bonnet</td>
<td>0.0304</td>
<td>4.4</td>
</tr>
<tr>
<td>Body</td>
<td>0.3139</td>
<td>44.1</td>
</tr>
</tbody>
</table>
The results obtained in this research are summarized as follows.
(1) A good agreement of the transmission-radiation coefficient $G$ was obtained in comparing single explosion excitation with firing operation of the engine. Thus, single explosion excitation is one of the most practical means to clarify the generation characteristics of combustion induced engine noise.

(2) Transmission-radiation coefficients calculated for three types of engines were compared from a viewpoint of the radiation characteristics of combustion impact noise.

(3) The high frequency components of the combustion impact noise were strongly transmitted through the gas excitation path in engine I.

(4) Vibration transmission characteristics show that the main radiation sources of the combustion impact noise in engine I are the cylinder upper cover, the cylinder rear cover and the gear case cover.

(5) The generation mechanism of combustion impact noise were investigated in detail calculating the vibration transmission coefficient and the noise radiation coefficient separately.

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References