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Harmonic Components of Cylinder Pressure Variation and Their Characteristics for Combustion Noise in Internal Combustion Engines

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Abstract

Combustion noise is a considerable detrimental problem in internal combustion engines. This investigation attempts to clarify the general characteristics of harmonic components in cylinder pressure variations which are the main exciting force of combustion noise. noise.

Cylinder pressure variation for different combustion behaviors and their harmonic components were calculated and an attempt was made to relate the various components.

The results indicate that the harmonic components can be approximately described by a linear function with four variables, namely four characteristic values of cylinder pressure variation. The coefficients of the four variables depend solely on the order number of engine revolution, and are independent of the combustion behavior and engine operating conditions.

1. Introduction

Combustion noise is a serious problem in internal combustion engines, especially diesel engines.

Much effort[1~4] has been made to reduce combustion noise, but much remains to be resolved.

Indicator diagrams or cylinder pressure variations are easily visible tools to evaluate and estimate the combustion noise and thermal efficiency. However, the relationship between cylinder pressure variations and the harmonic components of cylinder pressure variations, the exciting force in engine combustion noise, has not been completely determined .

In this paper, an attempt was made to clarify the relation between the harmonic components of cylinder pressure variations and characteristic values for the cylinder pressure variations such as the area of the cylinder pressure variation diagram $\int P d\theta$, the maximum rate of pressure rise $(\frac{dP}{d\theta})_{max}$, and others.

It was found that the logarithmic harmonic components of cylinder pressure variations, the cylinder pressure level CPL, can be described by a function with four variables. These variables, characteristic values, are easily obtained from cylinder pressure variation diagrams ; the area of cylinder pressure variation $\int P d\theta$, the pressure rise due to combustion ΔP,

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the maximum rate of cylinder pressure rise $(\frac{dP}{d\theta})_{max}$, and the maximum acceleration of cylinder pressure rise $(\frac{d^2P}{d\theta^2})_{max}$. It was also found that CPL below about the 9th order of engine revolutions is controlled mainly by $\int Pd\theta$ or P_{max}, between the 8th and 13th order by ΔP, between the 11.5th and 20.5th order by $(\frac{dP}{d\theta})_{max}$, and above the 16th or 20.5th order by $(\frac{d^2P}{d\theta^2})_{max}$.

2. Calculations

Cylinder pressure variations $P(\theta)$ for various burning rates were calculated with equation (1) based on the first law of thermodynamics and the state equation of gas.

$$\frac{dP}{d\theta}+k\frac{P}{V}\frac{dV}{d\theta}=\frac{k-1}{V}(C_{p_1}T_1\frac{dG_1}{d\theta}+C_pT\frac{dG_2}{d\theta}+\frac{dQ_b}{d\theta}+\frac{dQ_c}{d\theta}) \quad (1)$$

where, C_p : specific heat at constant pressure
G : weight of gas in cylinder
k : ratio of specific heats
P : cylinder pressure
Q_b : heat released by combustion
Q_c : heat loss by cooling
T : cylinder temperature
V : cylinder volume
θ : crank angle

The suffix 1 indicates intake, and 2 exhaust.

In the calculations, J. Reisacher's equation[5] which is a function of the temperature and excess air factor, was used for the ratio of specific heats in equation (1). The cooling loss Q_c at the combustion chamber wall was calculated by equation (2).

$$\frac{dQ_c}{dt}=hF(T-T_w)+0.362\left\{(\frac{T}{100})^4-(\frac{T_w}{100})^4\right\}F \quad (2)$$

where, F : heat transfer area
h : heat transfer coefficient
T_w : mean wall temperature of the combustion chamber

Of many expressions reported for h, the one reported by Woschni[6] is used in this paper.

The flow rate of the gas exchange in the cylinder $\frac{dG}{dt}$ is described as follows:

$$\frac{dG}{dt}=\mu f\phi\sqrt{2g\frac{p}{v}} \quad (3)$$

where, f : flow area at the valve seat
g : gravity acceleration
v : specific volume of gas in cylinder
ϕ : characteristic factor
μ : flow coefficient which was assumed to be 0.8 for all valve configurations and valve lifts.

Equation (3) is the basic equation for the flow rate of gas in or out of the cylinder, $\frac{dG_1}{d\theta}$ or $\frac{dG_2}{d\theta}$. The modified Wiebe's function[7] was used to describe the burning rate $\frac{dQ_b}{d\theta}$.

$$\frac{dQ_b}{d\theta}=\sum_{n=1}^{2}\left\{6.9\alpha_n Q_t(M_n+1)\left(\frac{\theta}{\theta_n}\right)^{M_n}\frac{1}{\theta_n}\exp\left\{-6.9\left(\frac{\theta}{\theta_n}\right)^{M_n+1}\right\}\right. \tag{4}$$

where, M_n : shape factor of combustion rate

Q_t : total heat release a cycle

α_n : heat ratio of premixed or diffusive combustions to Q_t

θ_n : combustion duration

n=1 : premixed combustion

n=2 : diffusive combustion

The form of the burning rate curve was systematically varied by changing M_n and θ_n, and is shown in figure 1. Fourier expansion of $P(\theta)$ is given as :

$$P(\theta)=\frac{1}{2}a_o+\sum_n\left(a_n\cos\frac{n}{2}\theta+b_n\sin\frac{n}{2}\theta\right) \tag{5}$$

$$\left.\begin{aligned}a_n&=\frac{1}{2\pi}\int_0^{4\pi}P(\theta)\cos\frac{n}{2}d\theta\\ b_n&=\frac{1}{2\pi}\int_0^{4\pi}P(\theta)\sin\frac{n}{2}d\theta\end{aligned}\right\} \tag{6}$$

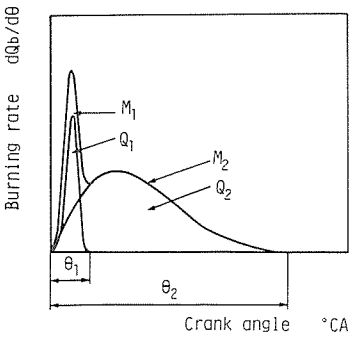

Fig. 1 Burning rate and its controlling parameters.

Equation (6) shows that 1/2 order harmonics of the engine revolutions is a basic order in four stroke-cycle engines. The cylinder pressure level for order n (CPL)n, the logarithmic harmonic components, is given as follows[2] ;

$$(CPL)_n=20\log\left(\frac{S_n}{2.886}\right)+200\ \text{dB} \tag{7}$$

where, the harmonic component of the cylinder pressure S_n equals $\sqrt{a_n^2+b_n^2}$.

The main engine dimensions in the calculations are 105 mm bore and 110 mm stroke.

3. Results of calculations and discussion

3.1 Combustion behavior and cylinder pressure level (CPL)

The main factors determining the shape of cylinder pressure variation include ignition timings and combustion rate curves.

Figure 2 shows the change in cylinder pressure variation for different ignition timings, θ_{ig}. The figure shows that some characteristic values of cylinder pressure variation, such as maximum pressure and the maximum rate of pressure rise, tend to increase with the advances in ignition timing.

The cylinder pressure level (CPL), the logarithmic harmonic component of cylinder pressure variation, is shown in figure 3.

With the advance in ignition timings, CPL lower than 200Hz increases, however it was shown that higher ones do not necessarily increase.

Figures 4 and 5 show the effects of the premixed combustion ratio α_1, and combustion duration θ_2 on CPL.

An increase in α_1, or a shortening of θ_2 results in a higher CPL component depending on

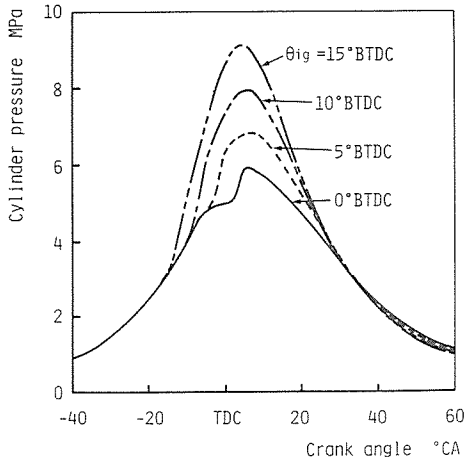

Fig. 2 Cylinder pressure variations for different ignition timings.

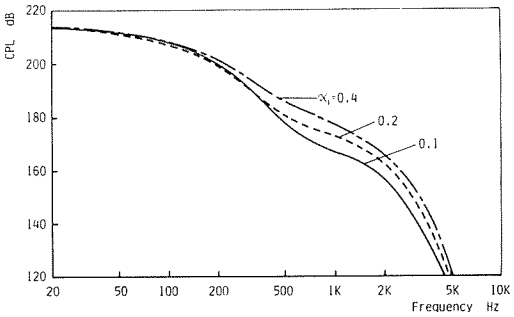

Fig. 3 CPL for different ignition timings.

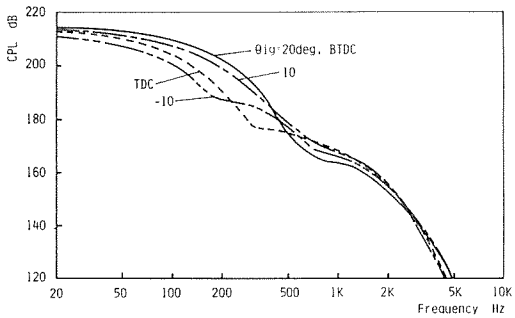

Fig. 4 CPL for different premixed combustion ratio.

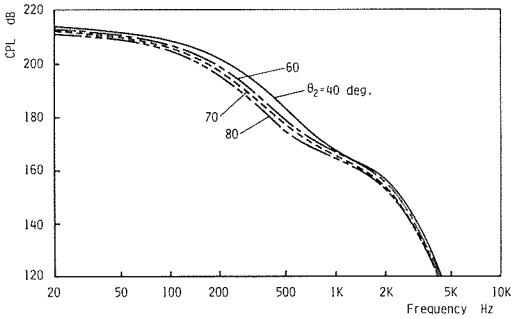

Fig. 5 CPL for different combustion duration.

the frequency or order number.

These results coincide with the rise in combustion noise in operating engines that occurs with advanced ignition timings, increased premixed combustion ratio, and shortened combustion.

3.2 Correlation between CPL and characteristic values of cylinder pressure variation

Cylinder pressure variations are easily observed and it is convenient to evaluated or estimate CPL and engine noise by the form of the cylinder pressure variation diagrams.

Characteristic values derived from the cylinder pressure variation include $\int Pd\theta$, ΔP, $(\frac{dP}{d\theta})_{max}$, and $(\frac{d^2P}{d\theta^2})_{max}$.

The relationship among CPL, $\int Pd\theta$, and $(\frac{d^2P}{d\theta^2})_{max}$ are shown in figures 6 and 7, with the data for different combustion conditions.

These figures show that, independent of the form of the cylinder pressure variation, $\int Pd\theta$ has a simple and positive relation with CPL in the lower order or frequency range and $(\frac{d^2P}{d\theta^2})_{max}$ as does in the higher order range.

To explain these results, the correlation coefficients between four characteristics values and CPL are shown in figures 8 and 9. The ordinate denotes correlation coefficients and the

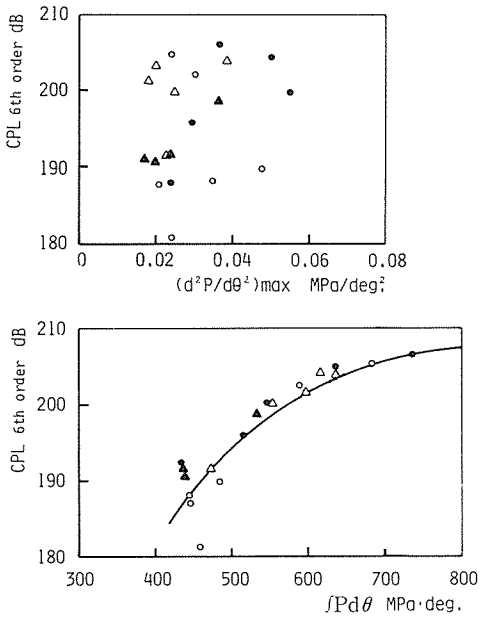

Fig. 6 Effects of characteristic values of $\int Pd\theta$ and $\left(\frac{d^2P}{d\theta^2}\right)_{max}$ on CPL (6th order).

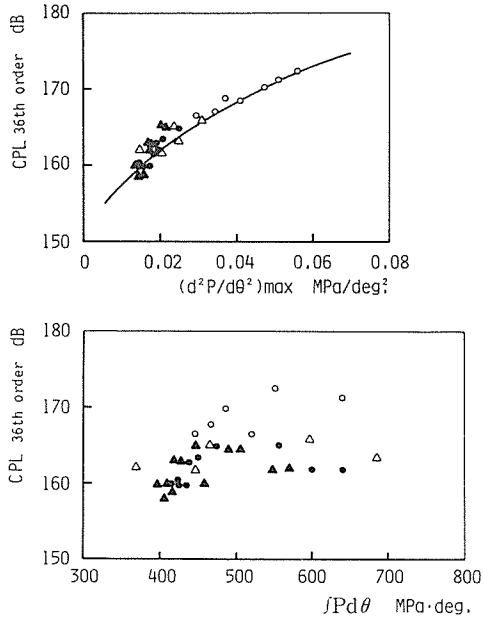

Fig. 7 Effects of characteristic values of $\int Pd\theta$ and $\left(\frac{d^2P}{d\theta^2}\right)_{max}$ on CPL (36th order).

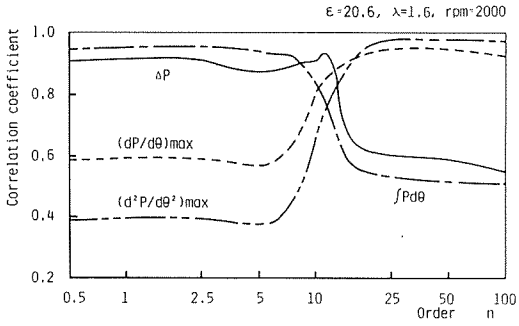

Fig. 8 Correlation coefficients between characteristic values and CPL.

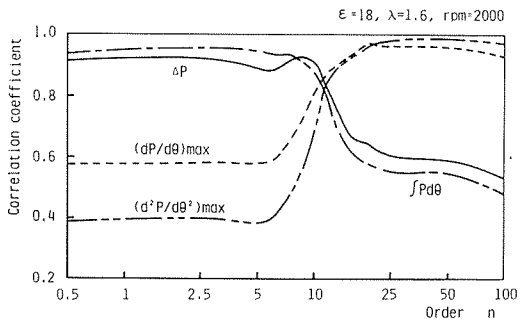

Fig. 9 Correlation coefficients between characteristic values and CPL.

abscissa the order of engine revolutions n. With the increasing order number the figures show that the characteristic values showing the highest correlation with CPL change in the order of: $\int Pd\theta$, ΔP, $\left(\frac{dP}{d\theta}\right)_{max}$, and $\left(\frac{d^2P}{d\theta^2}\right)_{max}$.

The order ranges where each factor dominates the control of CPL are:

$\int Pd\theta$	ΔP	$\left(\frac{dP}{d\theta}\right)_{max}$	$\left(\frac{d^2P}{d\theta^2}\right)_{max}$
$n<9.0$	$8.0<n<13$	$11.5<n<20.5$	$n>16\sim20.5$

These order ranges hold under a wide range of engine operating conditions, including loads, engine speeds, ignition timings, combustion rates, and compression ratios.

The $\int Pd\theta$ and the maximum pressure, P_{max}, show very similar correlations with CPL, with $\int Pd\theta$ showing slightly higher values.

3.3 Description of CPL with four characteristic values

The CPL is controlled by four characteristic values, and the n-th order harmonic component of cylinder pressure S_n is assumed to be described by a linear equation with four variables.

$$S_n = C_1 \int Pd\theta + C_2 \Delta P + C_3 \left(\frac{dP}{d\theta}\right)_{max} + C_4 \left(\frac{d^2P}{d\theta^2}\right)_{max} \quad (8)$$

The numerical series including Sn, $\int Pd\theta$, ΔP, $\left(\frac{dP}{d\theta}\right)_{max}$, and $\left(\frac{d^2P}{d\theta^2}\right)_{max}$ are obtained under various engine operating conditions, and the four coefficients C_1, C_2, C_3 and C_4 are calculated for equation (8).

The four coefficients are shown in figures 10, 11, 12 and 13. The symbols in the figures correspond to different engine operating conditions: compression ratios, excess air factors, and engine speeds.

These results indicate that the four coefficients are determined by the order number and are nearly independent of the combustion behavior and engine operating conditions. The n-th order harmonic component of the cylinder pressure S_n can be described by a linear

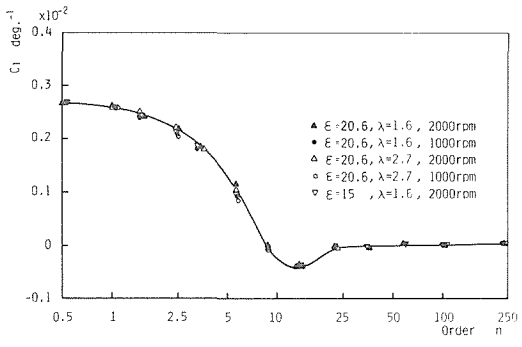

Fig. 10 Coefficient C_1.

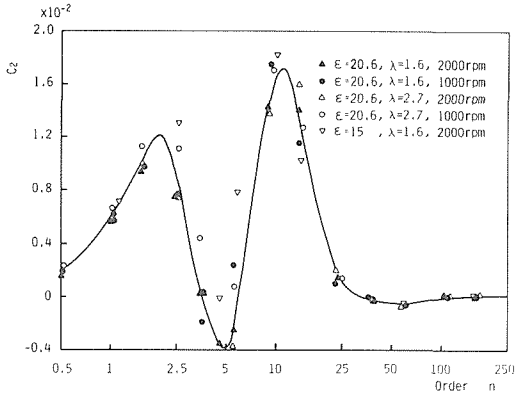

Fig. 11 Coefficient C_2.

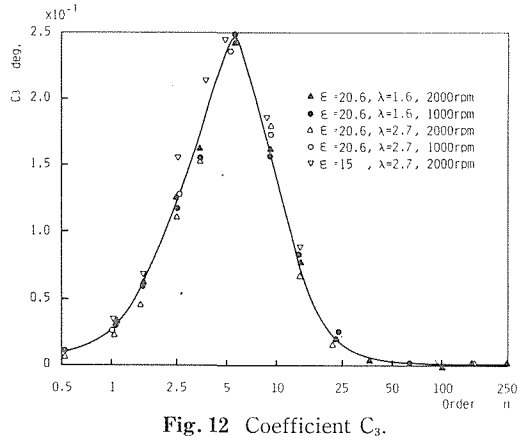

Fig. 12 Coefficient C_3.

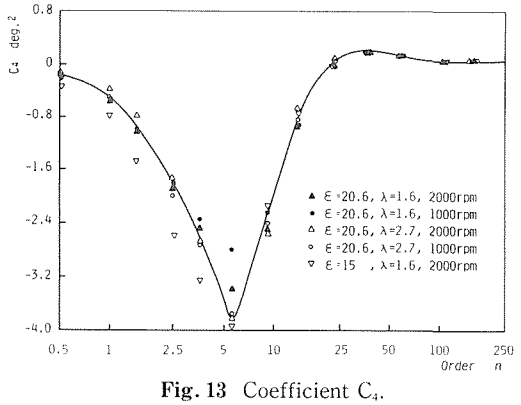

Fig. 13 Coefficient C_4.

equation with four variables, and four characteristics values.

In addition, the coefficient for $\int Pd\theta$, C_1, is larger below about the 9th order range, corresponding to $\int Pd\theta$ which has a better correlation with CPL below about the 9th order. The coefficient for $(\frac{d^2P}{d\theta^2})_{max}$, C_4, is also relatively large above the 16th order. This indicates that $(\frac{d^2P}{d\theta^2})_{max}$ mainly controls the high frequency CPL and therefore high frequency combustion noise.

4. Conclusion

The results of this paper can be summarized as follows:

1) A relationship was established between CPL and four characteristic values describing the cylinder pressure and variation diagram.

2) Harmonic components of cylinder pressure variations are described by a linear function with four variables, and four characteristic values.

3) In this case, the coefficients of the four variables depend solely on the order of engine revolutions and are independent of combustion behavior and engine operating conditions.

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References

1) T. Priede: SAE Trans. 800534 (1980), 2039
2) N. Miyamoto et al.: Trans. of the JSME 38-307 (1972), 865
3) H. List: The Development of Modern Diesel Engines, JSME (1968)
4) T. Murayama et al.: Trans. of the JSME 42-358 (1976), 1877
5) J. Reisacher: MTZ 27/10 (1966)
6) G. Woschni: MTZ 2/4 (1964)
7) G. Sitkei: Kraftstoffaufbereitung und Verbrennung bei Dieselmotoren, Springer (1964)