디이젤기관에 있어서 실린더 압력변동의 하모닉성분 특성

Characteristics of Harmonic Components of Cylinder Pressure Variation in Diesel Engine.

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초 록

엔진소음은 내연기관에서 중요한 관심사중의 하나이다.

본 연구는 연소소음에 주요한 영향을 미치는 실린더 압력변동에 있어서 주파수 성분의 일반적 특성을 밝혔다.

각기 다른 연소거동과 그들의 주파수성분 분석을 위한 실린더 압력변동의 계산방법을 모색하였다.

주파수 성분은 4종류의 변수, 즉 실린더 압력변동의 4종류 특성치를 갖는 선형 연소함수에 의하여 근사적으로 기술될 수 있음을 밝혔다.

마지막으로 4종류의 변수의 상관관계는 연소거동이나 엔진운전조건에 관계없이 단지 엔진회전수의 차수(Order)에만 의존함을 밝혔다.

NOMENCLATURE

CPL : Cylinder pressure level
S_p : Specific heat at constant pressure
F : Heat transfer area
l : Flow area at the valve seat
G ;: Wight of gas in cylinder
g : Gravity acceleration
h : Heat transfer coefficient
m_1, m_2 : Shape factor of premixed or diffusive combustions
P : Cylinder pressure
Q_b : Heat released by combustion
Q_c : Heat loss by cooling
Q_T : Total heat release a cycle
Sn : Harmonic component of the cylinder pressure
T : Cylinder temperature
Tw : Mean wall temperature of the combustion chamber
V : Cylinder volume
v : Specific volume of gas in cylinder
R : Ratio of specific heats
θ : Crank angle
θ_1, θ_1 : Duration of premixed or diffusive combustions
θig : Ignition timing
ϕ : Characteristic factor

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μ : Flow coefficient which was assumed to be 0.8 for all valve contigurations and valve lifts

α_1, α_2 : Heat ratio of premixed or diffusive combustion to Q_t

λ : Ratio of air excess

ϵ : Compression ratio

ΔP : Pressure rise due to combusion

$\int P d\theta$: Area of cylinder pressure variation

$\left(\frac{dP}{d\theta}\right)_{max}$: Maximum ratio of culinder pressure rise

$\left(\frac{d^2P}{d\theta^2}\right)_{max}$: Maximum acceleration of cylinder pressure rise

I. INTRODUCTION

Combustion noise is a serious concern 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 the useful 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, exciting force in engine combustion noise, has not been completely understood.

In this paper, an attempt has been 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 $\left(\frac{dP}{d\theta}\right)$ max, and others.

It was found that the logarithmic harmonic components of cylinder pressure variations, ie. 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, ie. area of cylinder pressure variation $\int P d\theta$, the pressure rise due to combustion ΔP, the maximum rate of cylinder pressure rise $\left(\frac{dP}{d\theta}\right)$ max, and the maximum acceleration of cylinder pressure rise $\left(\frac{d^2P}{d\theta^2}\right)$ max. It was also found that CPL below about the 9th order of engine revolutions is controlled mainly by $\int P d\theta$ or Pmax, between the 8th and 13th order by ΔP between the 11.5th and 20.5th order by $\left(\frac{dP}{d\theta}\right)$ max, and that above the 16th or 20.5th order by $\left(\frac{d^2P}{d\theta^2}\right)$max.

2. CALCULATIONS

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

$$\frac{dP}{d\theta}+K\frac{P}{V}\frac{dV}{d\theta}=\frac{K-1}{V}\left(C_{p1}T_1\frac{dG_1}{d\theta}+C_pT\frac{dG_2}{d\theta}+\frac{dQ_b}{d\theta}+\frac{dQ_c}{d\theta}\right) \quad \cdots\cdots\cdots\cdots (1)$$

Where, Cp : specific heat at constant pressure
G : weight of gas in cylinder
k : ratio of specfic heats
P : cylinder pressure
Qb : heat released by combustion
Qc : heat loss by cooling
T : cylinder temperature
V : cylinder volume
θ : crank angle

The suffix 1 indicates the intake, and 2 the exhaust.

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

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

Where, F : heat transfer area
h : heat transfer coefficient
Tw : 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:

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

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

Eq.(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 $\frac{dG_b}{d\theta}$.

$$\frac{dQ_b}{d\theta}=\sum_{n=1}^{2} 6.9\,\alpha_n Q_t(m_n+1)\left(\frac{\theta}{\theta_n}\right)^{m_n}\frac{1}{\theta_n}\,exp\left\{-6.9\left(\frac{\theta}{\theta_n}\right)^{m_n+1}\right\} \quad \cdots\cdots\cdots\cdots (4)$$

where, m_n : shape factor of combustion rate
Qt : total heat release a cycle
α_n : heat ratio of premixed or diffusive combustions to Qt
θ_n : combustion duration
n=1 : premixed combustion
n=2 : diffusive combustion

Detailed methods of calculation for P(θ) or indicated heat efficiency using Wiebe's function was reported elsewhere (8).

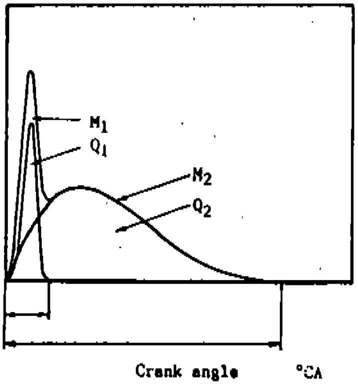

Fig. 1 Burning rate and its controlling parameters

The form of the burning rate curve was systematically varied by changing m_n and θn, as is shown in fig.1. Fourier expansion of P(θ) is given as

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

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

Eq.(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, ie. the logarithmic harmonic components, is given as follows (2).

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

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

Unit of P(θ) is Kg/Cm^2 in Eq.(5), and basic pressure Po=2x10^{-4} dyne/Cm^2 in Eq.(7).

The calculation of Eq.(6) was done by Simpson's numerical integration where the main engine dimensions in the calculations are 105mm bore, 110mm stroke, and stroke volume of 860cc.

3. RESULTS AND DISCUSSIONS

3.1 Combustion behavior and cylinder pressure level(CPL)

The main factors that determine the shape of cylinder pressure variation include ignition timing and combustion rate.

Fig.2 shows the change of cylinder pressure variation for different ignition timings, θig. This shows that some characteristic values of cylinder pressure variation, such as maximum pressure and the maximum rate of pressure rise tend to increase as ignition timing advances.

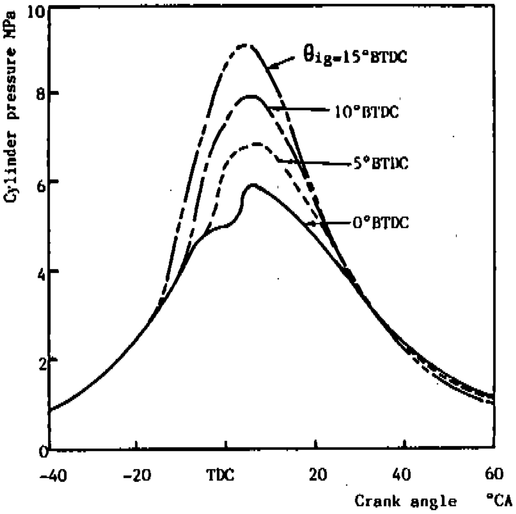

Fig.2 Cylinder pressure variations for different ignition timings

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

With advance in ignition timing, CPL lower than 200Hz increases, however higher ones do not necessarily increase.

Figs.4 and 5 show the effects of the premixed combustion ratio α_1, and combustion duration θ2 on CPL.

An increase in α_1, or a shortening of θ2 results in a higher CPL component depending on 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.

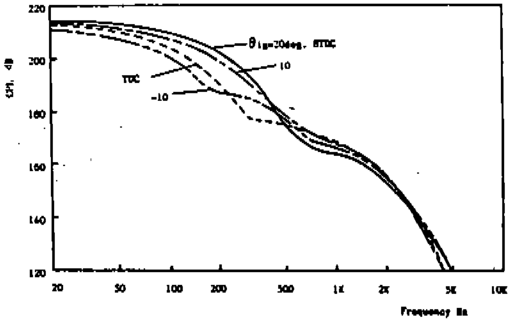

Fig.3 CPL for different ignition timings

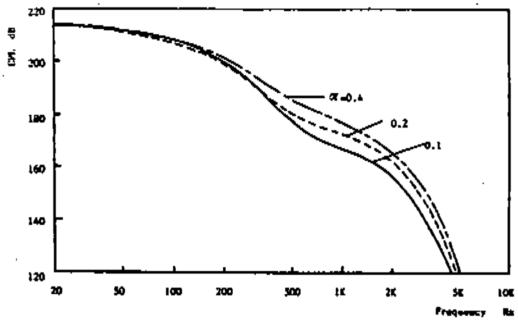

Fig.4 CPL for different premixed combustion ratio

3.2 Correlation between CPL and characteristic values of cylinder pressure variation.

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

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

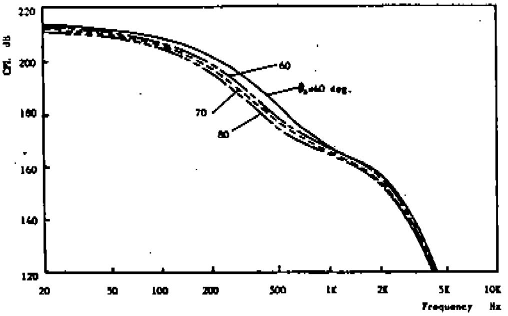

Fig.5 CPL for different combustion duration

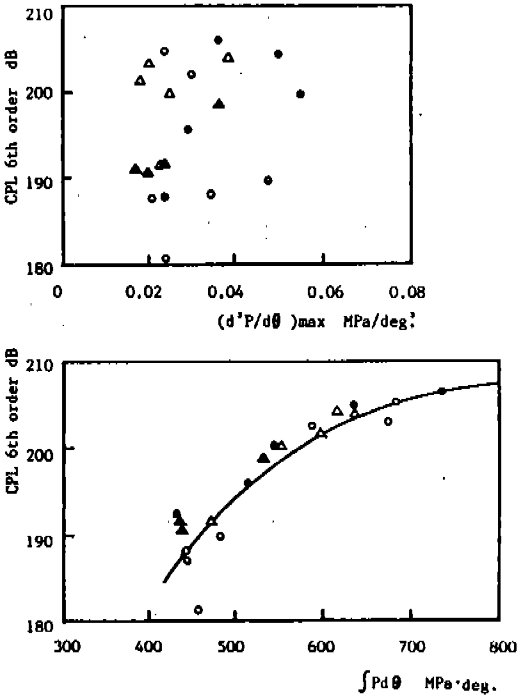

Fig.6 Effects of characteristic values of $\int Pd\theta$ and $(d^2P/d\theta^2)_{max}$ on CPL 6th order

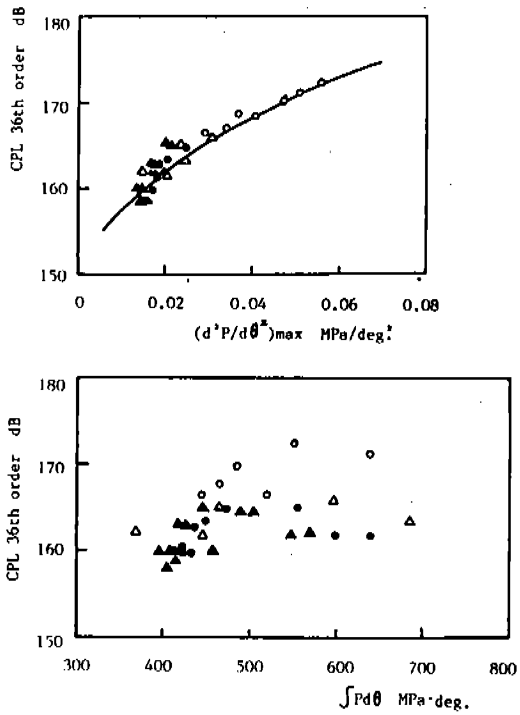

Fig.7 Effects of characteristic values of $\int Pd\theta$ and $(d^2P/d\theta^2)_{max}$ on CPL 36th order

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

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 with $\left(\frac{d^2P}{d\theta^2}\right)$ max against CPL in the higher order range.

To explain these results, the correlation coefficients between four characteristics values and CPL are shown in figs.8 and 9. The ordinate denotes correlation coefficients and the abscissa the order of engine revolutions n. With increasing order number the figures show that the characteristic value 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.

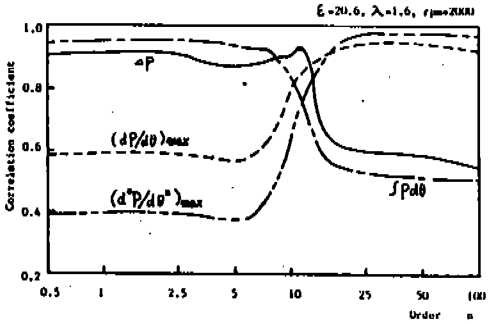

Fig.8 Correlation coefficients between characteristic values and CPL

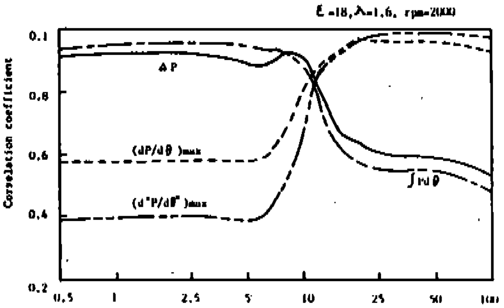

Fig.9 Correlation coefficients between characteristic values and CPL

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

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

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

The $\int Pd\theta$ values and the maximum pressure, Pmax, show very similar correlations with CPL, with $\int Pd\theta$ slightly higher.

3.3 Description of CPL with four characteristics values

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

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

In equation (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 the simultaneous equations.

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

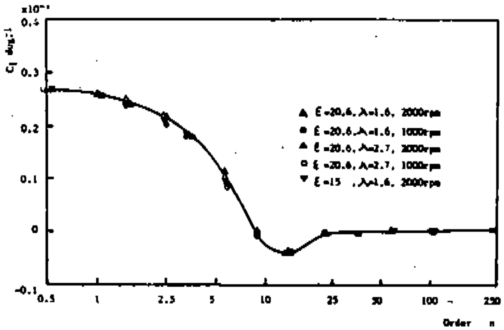

Fig.10 Coefficent C_1

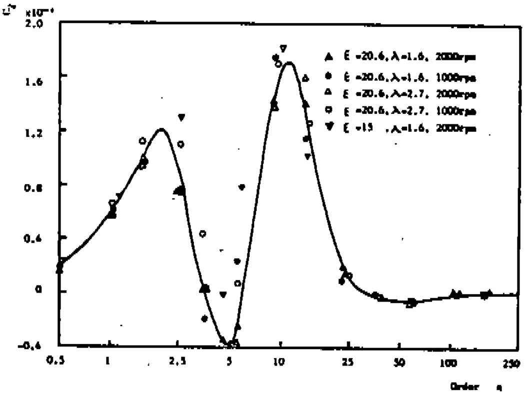

Fig.11 Coefficent C_2

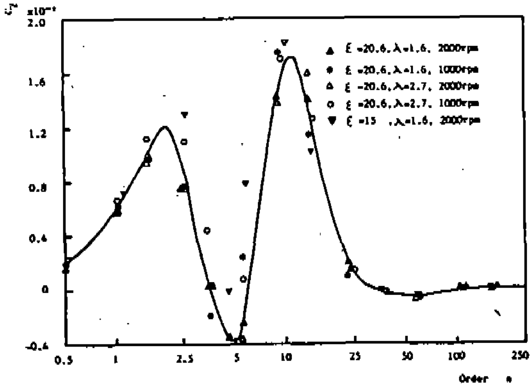

Fig. 12 Coefficent C_3

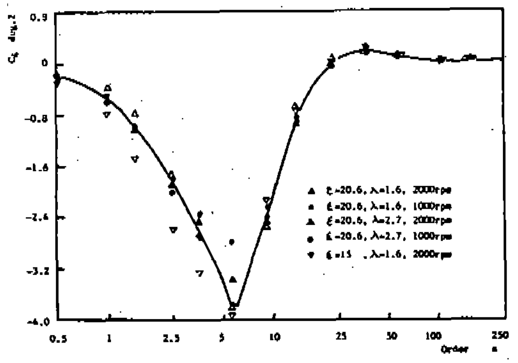

Fig. 13 Coefficent C_4

factor, and engine speeds.

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

In addition, the coefficient for $\int P d\theta$, C_1, is larger below about the 10th order range, corresponding to $\int P d\theta$ having a better correlation with CPL below about the 9th order. The coefficient for $\left(\frac{d^2P}{d\theta^2}\right)$ max, C_4, is also relatively large above the 16th order. This indicates that $\left(\frac{d^2P}{d\theta^2}\right)$ max mainly controls the high frequency CPL, and $\left(\frac{d^2P}{d\theta^2}\right)$ max controling high-frequency combustion noise.

4. CONCLUSION

Results can be summarized as follows:

1) A relationship was established between CPL and four characteristic vlaues describing the cylinder pressure variation diagram.
2) Harmonic components of cylinder pressure variations are descrbied by a linear-combination function with four variables, four characteristic values.
3) In this case, the coefficients of the four variables depend only on the order of engine revolutions and are independent of combustion behavior and engine operating conditions.

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