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Study on the Cycle-by-Cycle Variation in Diesel Engines*

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In order to study the cycle-by-cycle variations of combustion in a diesel engine, a continuous data acquisition system utilizing the analog computing circuits was developed and its accuracy was verified satisfactorily. Preliminary experiment proved that the amount of injected fuel per cycle could be measured indirectly by the integrated value of the injection nozzle lift. Then, applying the whole system to a two-stroke diesel engine, the necessary data including the indicated mean effective pressure etc. were collected and analyzed statistically. The result indicates that the irregularity of amount of injected fuel per cycle, which is subjected to the varying characteristics of the injection system concerned, mainly governs the variation of the indicated mean effective pressure.

1. Introduction

Some phenomena observed in the running internal combustion engines seem to have an irregularity due to cycle variation inherently, even under constant operating condition. Cycle-by-cycle variations in such parameters as maximum cylinder pressure, flame propagation speed and indicated mean effective pressure have been measured to clarify the mechanism of cycle variation in combustion in Otto engines by many investigators^{(1)~(4)}. As for diesel engines, however, it seems that little work has been done on this problem. The fact does not always mean that the influence of cycle variation on the combustion in diesel engines is of little importance. For example, in the analysis of heat release, as is known well, it is hard to get accurate result with the data of a few cycles because of the existence of cycle variation. When the stability or the reliability of data is required, the quantitative determination of irregular phenomena as well as the knowledge about the contribution of each relating factor to the irregularity have to be considered.

Here is presented a measurement and analysis on the cycle variation of a diesel engine by means of random data analysis techniques, where four parameters are chosen to represent the cycle variation. They are amount of injected fuel, integrated value of injection nozzle lift, in-

dicated mean effective pressure, and maximum cylinder pressure.

Variations in the parameters were analyzed statistically and the values such as standard deviations, coefficients of variation, and cross-correlation coefficients between each parameter were obtained. In addition, power spectral density functions, and coherence functions were also calculated to study the time history.

The data acquisition system used here, which has been another important aim of this study, has been developed by us and it has its sufficient usefulness proved for the measurement of successive cycle variation with required accuracy.

2. Method of data acquisition and processing

2.1 Data acquisition and processing system

It was proved through preliminary experiments that the amount of injected fuel in each cycle could be estimated by the integrated value of injection nozzle lift, thus we could avoid difficulty of direct measurement. Data of three other parameters are respectively calculated from the transducer output concerned directly by the analog computing circuit, considering that the data processing speed is more significant than the calculating accuracy to obtain the successive data for each parameter on real time basis, while the total accuracy of the system is mainly affected by the accuracy of transducers used.

A block diagram of the system applied to the engine experiments is shown in Fig. 1. Indicated mean effective pressure, and time integrated value of injection nozzle lift are calculated directly on real time basis by the analog computing circuit, using the analog values which are supplied from the transducers of the cylinder pressure, nozzle lift of fuel injector, and

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piston speed. To investigate the interrelationship between each calculated parameter, two similar devices are employed. A timing slit which is connected with a crank shaft directly supplies the control pulses to the analog computing circuits and a magnetic tape recorder respectively. In the play back of recorded data, the control pulses are used as an index for the data of every cycle, and recorder speed is reduced to one-twentyth of recording speed in order to match its speed to that of puncher. A pair of recorded results is converted to a digital value through an A-D converter alternatively and is stored in the punched tape. The calibration data and experimental condition are also punched on the same tape. Finally, the tape is fed to a general purpose digital computer for the processing of statistical analysis.

This system is able to carry out a more complicated processing of data than the direct processing system using a mini-computer⁽⁵⁾ or a pulse height analyzer, and has advantages of low cost to make, flexibility in use, and simple constitution.

2.2 Analog computing circuit

Fig.2 shows a block diagram of the analog computing circuit prepared for this experiment. A circuit including S/H 1 and a summing amplifier acts to reject the voltage offset of input E_x from a transducer at every start of cycle calculation. A part of circuit in the integrator is used in common with a peak-detector. So, it is able to select its function with a switch. Prior to resetting the integrator, the value produced in this component is transferred to S/H 2, and held there through a cycle as an output. Starting from the trigger pulse, two kinds of control pulses are generated by the control circuit composed of monostable multi-vibrators and inverters, and they are supplied to the sample-hold circuit and the integrator to control its function. By switching the connection of each component in the computing circuit, the following operations can be carried out; integration, integration after multiplication, and peak-detection.

2.3 Way of analog calculation

Indicated mean effective pressure P_i is defined as,

$$P_i = W_i/V = (1/V) \oint P dv \quad (1)$$

where, W_i is indicated work developed in a cycle, V is stroke volume, and P is cylinder pressure. Equation (1) can be rewritten in the following integral.

$$P_i = (1/V) \oint P (dv/dt) dt = (1/L) \oint P u dt \quad (2)$$

where, L is piston stroke and u is piston speed. If piston speed is given in analog value, the integration expressed above can be realized easily by an analog computing circuit.

Fig.3 shows a schema of the piston

speed transducer developed for this purpose. (5) and (6) compose a slider-crank mechanism which has similar proportion to the real engine, and a coil (3) wound on a bobbin (4) is connected with a slider directly, and it moves in a uniform magnetic field generated between each magnetic pole (2). Then, induction voltage which is proportional to the piston speed is generated in this coil. The errors caused by the inner resistance and the self-induction of coil can be reduced by amplification to a negligible order using a high input impedance amplifier. Using the proportional relation between the maximum piston speed in a cycle and the revolution speed of engine,

Fig.1 Block diagram of data acquisition and processing system

Fig.2 Block diagram of analog computing circuit

Fig.3 Schema of piston speed transducer

the conversion gain of this transducer is calibrated by measured maximum output at each speed.

Fig.4 shows the waveforms exhibiting a calculation process of indicated mean effective pressure in the analog computing circuit.

The relation between the integrated value of injection nozzle lift and the amount of injected fuel is investigated independently. The amount of injected fuel per cycle is obtained to integrate the fuel injection rate which is measured by the method of injection rate indicator proposed by W.Bosh. The integrated value of injection nozzle lift is also calculated with the analog computing circuit to integrate the nozzle lift which is detected with a relative displacement indicator of moving core type. The maximum cylinder pressure is obtained by the peak-detector.

3. Accuracy of measurement

3.1 Analog computing circuit

The accuracy of this system consists of a sum of errors in the components included, such as summing amplifiers, integrators, sample-hold modules, and inverters, and the accuracy of each component is determined by the electric characteristics of the operational amplifier used and the accuracy of circuit constants composing its feed back network. The electric characteristics of the operational amplifiers such as drift, slew rate, open-loop gain, and noise cause a negligibly small error, because the calculation period is short, the frequency of input is low, the gain of each component is small, and the offset voltage is adjusted prior to the beginning of each experiment. The accuracy of feed back network is decided by its adjustment which has been checked prior to the beginning of each experiment using a digital voltmeter. So, its accuracy depends on the accuracy of the digital voltmeter used in calibration.

The accuracy of each component is as follows; the errors of summing amplifiers, sample-hold modules, and peak-detectors are 0.2%, those of high input impedance amplifiers are 0.3%, those of integrators are 1.2%, and those of multipliers are 0.5%.

3.2 Data acquisition and processing system

Each error of the magnetic tape recorder, multiplexer, and A-D converter which is determined by the accuracy of calibration voltage and A-D converter, is 0.3% respectively. The noise included in the magnetic tape recorder output signal is statistically analysed by a similar procedure to other analysis.

The result shows that the standard deviation of noise is less than 5mV, noise is white one, and a pair of data has no correlation with each other as far as noise is concerned. The rated output of magnetic tape recorder is 1.0V, and the

resolution of A-D converter is 1mV,

3.3 Accuracy concerned with steady-state value

The cylinder pressure transducer used in this experiment is a strain gauge type, its accuracy being 2%.

In order to estimate the accuracy of piston speed transducer, the output signal of transducer which is driven at constant speed is recorded by an electro-magnetic oscillograph. The recorded waveform agrees with the theoretical value within an error of 1%.

The setting error of the piston speed transducer related to the crank angle brings a large error into the result of indicated mean effective pressure calculation, so the crank angle of transducer must be made to be agree with a crank shaft of engine precisely. In this experiment, this was adjusted to within a half degree of crank angle.

Fig.5 shows a comparison of indicated mean effective pressure measured by the analog computing circuit and brake mean effective pressure measured by a dynamometer. Since each value plotted in the figure is shown in a line, non-linearity in the characteristics of transducers and computing circuit can be ignored. Considering that the pumping loss of engine measured by Willan's method and motoring method is 0.25 Kg/cm², the error of indicated mean effective pressure calculated by the computing circuit is estimated at

Fig.4 Computing waveform of indicated mean effective pressure

Fig.5 Comparison of indicated mean effective pressure and brake mean effective pressure

less than 0.15 Kg/cm^2 .

The integrated value of fuel injection rate was examined to compare with amount of injected fuel measured by a mass flow meter at the same time. The value obtained by the fuel injection rate indicator was a little greater than the value obtained by the mass flow meter. It is considered that the difference between both amounts of injected fuel is due to the effect of friction of fluid as well as the reflected pressure wave in the measuring pipe of the fuel injection rate indicator. Therefore, the conversion gain of fuel injection rate indicator was corrected accordingly based on this result. Consequently the accuracy of amount of injected fuel obtained by fuel injection rate indicator is within 2% which is comparable to the total error of computing circuit.

Errors estimated for integrated value of injection nozzle lift as well as maximum cylinder pressure with the accuracy of transducers and analog computing circuit are 3% and 4% respectively.

3.4 Accuracy concerned with analysis of variation

The accuracy described above is the one concerned with steady state value. But, in case of analysing the variation, the noise which is originated from the transducer and is comparable to the value of variation itself seems to become more significant than in the case of steady state error as stated above.

The analog computing circuit itself causes no error based on noise and the integrator reduces the influence of transducer's noise. But the sample-hold and peak-detector are inclined to be affected by the transducer's noise, due to its high response ability.

In order to estimate the error of indicated mean effective pressure and maximum cylinder pressure under test condition, the variation in the motoring operation was measured. Errors expressed in terms of standard deviation are 0.024 Kg/cm^2 and 0.26 Kg/cm^2 respectively. Since these values include the effect of variation in cylinder pressure of each cycle, which is fluctuating during motoring operation, the error caused by the transducer's noise itself is not greater than above value.

The errors due to the noise of fuel injection rate indicator as well as of the transducer of injection nozzle lift were measured under no fuel injection, and they are 30 mV r.m.s. respectively. The maximum rate of these errors in the experimental results is 0.5%, while the maximum rate of errors due to magnetic tape recorder's noise is 0.3%.

Judging from the results stated above, the data acquisition and sampling system proposed here is considered to have a sufficient accuracy for the purpose of investigating the variation, although it may not be accurate enough to investigate the steady state value.

4. Test rig for application

Using the data acquisition and processing system as mentioned above, the cycle-by-cycle variation observed in a two-stroke, pre-combustion chamber type diesel engine was investigated statistically. This variation is represented in terms of amount of injected fuel, indicated mean effective pressure, and maximum cylinder pressure.

The dimensions of the engine used are given in Table 1. The operating speed of engine was kept constant by a dynamometer which controlled its load absorption, so that no mechanical governor was attached to the fuel injection pump in order to eliminate the fluctuation of injected fuel quantity, which otherwise would have been caused by speed control. The operating load of engine was adjusted by a rack of fuel injection pump.

The experimental conditions were as follows; the engine speed is fixed at 1400 rpm, the load is adjusted constant corresponding to three steps of injection pump rack position. They are set at 17.5, 18.5, and 19.5 in order of increasing load. The experiments were carried out in two ways; in one case the rack is fixed, while in the other case the rack is driven in sine wave motion of amplitude 0.5 around the set rack position.

After sufficient warming up of engine to reach the steady state operation, the data of successive 1000 cycles were sampled and they were analysed statistically by a computer.

5. Experimental results and considerations

For the convenience of explanation, the symbols Q_f , L_i , P_i , and P_{max} are used to express the amount of injected fuel, integrated value of injection nozzle lift, indicated mean effective pressure, and maximum cylinder pressure respectively.

5.1 Relation between Q_f and L_i

Used injection nozzle has such static characteristics that the effective opening area is proportional to the needle lift of the injection nozzle. So, it is supposed that the waveform of needle lift and in-

Table 1 Specifications of engine

Make, Model	VICTOR AUTO, Vic 16
Engine type	Two-stroke cycle diesel
Type of combustion chamber	pre-combustion chamber
Type of scavenge	crank case compressed loop scavenge
Compression ratio	22
Cylinder bore/stroke, number	82/94mm, 1
Rated horse power	6Ps/2000rpm
Fuel injection pump plunger	DIESEL KIKI 1110-900. PE-A 31101-142
Injection nozzle	4SNP2-M-10C

jection rate are quite identical with each other, as shown in Fig.6. Therefore it seems that a linear relationship holds between Q_f and Li and that the variation of Q_f is able to be estimated by the variation of Li .

The calculated results of mean values μ , standard deviations σ , coefficients of variation σ/μ , and cross-correlation coefficients ρ for Q_f and Li are presented in Table 2.

The relation between both mean values is shown in Fig.7. Q_f is proportional to Li in this test range. The inclines at each experimental point on this curve, which are obtained by regression analysis, are distributed within 0.0132 and 0.0146 ms.st/mm². These values agree well with the incline of the curve itself and this value is 0.0138 ms.st/mm². For these reasons, it is confirmed that there is a linear relation between Q_f and Li .

As shown in Table 2, the coefficients of variation of the amount of injected fuel distribute within the range of about 3% to 15% when the rack is fixed.

As to the cross-correlation coefficients, they are more closely related to the standard deviation than to the rack position and will increase with an increasing standard deviation. This increase is considered to be caused by the following reasons; even if Q_f has no cycle variation, Li fluctuates in itself and this fluctuation is reduced relatively with an increasing of Q_f 's cycle variation.

The power spectra and the coherence functions between input Q_f and output Li are shown in Fig.8 and Fig.9. The horizontal axis in these figures indicates the normalized frequency, i.e. a frequency multiplied by the sampling interval $\Delta t = 42.9$ ms and this normalized frequency is consequently equal to the reverse number of cycles of engine within one period. For example, the value of $1/2$ means a frequency of 11.7 Hz. The power spectral density for longitudinal axis is also normalized by dividing the power spectral density with square mean value, and the mean value of normalized power spectrum over the entire frequency range is equal to 1.

As shown in Fig.8 at the rack position of 17.5, both power spectra of Q_f and Li are almost white noise and have peaks at the frequencies near $1/2$ and $1/3$. The coherence between these two parameters is

not so strong, but at the peaks of power spectra it is comparatively strong.

As shown in Fig.9 at the rack position of 19.5, a large power distributes widely around the frequency of $1/4$. This indicates that the phenomena are fluctuated with a period of one time in every 4 cycles. A wholly high coherence means that

Fig.6 Waveform of needle lift and injection rate

Table 2 Calculated results for Q_f and Li

rack position	Q_f				Li				ρ
	μ mm ³ /st	σ mm ³ /st	σ/μ %		μ mm ms	σ mm ms	σ/μ %		
fixed rack	17.5	10.3	0.298	2.90	0.185	0.005 18	2.80	0.758	
	18.5	13.8	0.452	3.25	0.232	0.007 14	3.08	0.873	
	19.5	16.4	2.54	15.5	0.262	0.034 8	13.3	0.993	
driven rack	17.5	11.3	0.994	8.80	0.191	0.014 9	7.80	0.926	
	18.5	—	—	—	—	—	—	—	
	19.5	16.3	3.02	18.5	0.268	0.043 7	16.3	0.993

Fig.7 Relation between mean values of Q_f

Fig.8 Power spectra and coherence function at rack position of 17.5

Fig.9 Power spectra and coherence function at rack position of 19.5

Q_f and L_i have a very close correlation to each other. Just as at the rack position of 17.5, a low coherence at the frequency near $1/20$ indicates that factors out of Q_f cause the great part of L_i 's cycle variation at this frequency.

From the above it is confirmed that Q_f and L_i have linear relation between them, and that, particularly under the condition of the cycle variation being great, the cycle variation of Q_f is estimated accurately from that of L_i . Even if the cycle variation and cross-correlation coefficient are small, the inter-relationship between them is estimated from the features of power spectra.

5.2 Relation between L_i and P_i

The results of data analysis for P_i and L_i are shown in Table 3.

All mean values in this table are represented in Fig.10. P_i is proportional to L_i except in the neighbourhood of the upper limit of L_i , where non-linearity increases. This trend agrees with the trend which is observed in the relation between brake mean effective pressure and amount of injected fuel. In this non-linear region, the correlation is low as indicated by the cross-correlation coefficients in Table 3.

The power spectra of P_i and L_i when the rack position is 17.5 are shown in Fig.11. All power spectra are similar to each other and have peaks at the same frequency, and the coherence is strong where power spectrum is large. The trend mentioned above is similar when the rack position is 19.5 as shown in Fig.12.

From these characteristics of power spectra and coherence function, it is considered that the cycle variation of indicated mean effective pressure is mainly caused by the cycle variation of amount of injected fuel.

Although, however, the comparison of power spectra which are not normalized indicates that the value at the rack position of 19.5 is considerably larger than the value at the rack position of 17.5, the difference of the coherence function is not so large as the difference of each power spectra. For example, at the rack position of 17.5, the peak value of P_i 's power spectra at the frequency near $1/3$ is $0.024 (\text{Kg/cm}^2)^2$, while at the rack position of 19.5 it is $0.118 (\text{Kg/cm}^2)^2$, that is to say, the latter is about five times greater than the former. On the other hand, the corresponding value of coherence at the rack position of 17.5 is 0.983 and at the rack position of 19.5 it is 0.901; that is to say, the latter is smaller than the former inversely. Then the causes giving non-linear characters in the cycle variation of indicated mean effective pressure may be considered not to be the same at the rack position of 19.5 as at the rack position of 17.5.

5.3 The maximum cylinder pressure

The following are shown in Table 4;

the cycle variation of P_{max} is approximately constant against the variation of amount of injected fuel at any load, coefficients of variation of P_{max} are distributed from 3% to 2%, and close correlation does not exist between these parameters as low cross-correlation coefficients indicate.

The power spectra of each L_i and P_{max} in the condition when the rack is driven around a rack position of 17.5 with sine wave are shown in Fig.13. No matter how the power spectrum of L_i distributes, the power spectrum of P_{max} shows almost con-

Table 3 Calculated results for L_i and P_i

rack position		L _i			P _i			ρ
		μ mm ms	σ mm ms	σ/μ %	μ Kg/cm ²	σ Kg/cm ²	σ/μ %	
fixed rack	17.5	0.136	0.004 10	3.01	2.00	0.073 8	3.69	0.848
	18.5	0.169	0.006 09	3.60	3.00	0.119	3.95	0.813
	19.5	0.249	0.015 8	6.34	4.10	0.213	5.19	0.791
driven rack	17.5	0.166	0.012 1	7.28	2.75	0.226	8.78	0.960
	18.5	0.211	0.016 5	7.84	3.44	0.265	7.71	0.937
	19.5	0.256	0.029 2	11.4	4.10	0.285	6.94	0.889

Fig.10 Relation between mean values of L_i and P_i

Fig.11 Power spectra and coherence function at rack position of 17.5

Fig.12 Power spectra and coherence function at rack position of 19.5

stant distribution over the entire frequency range; even where power spectrum of L_i is very large, the power spectrum of P_{max} is small, and in addition, the coherence is generally very weak. The similar results are observed also in the spectral analysis of P_i and P_{max} .

Then, it is considered that P_{max} fluctuates randomly even if the amount of injected fuel has no cycle variation, and that the cycle variation of P_{max} has little influence on the cycle variation of P_i .

5.4 Estimation of non-linear component

Assume that a system operates under stationary random input $x(t)$, where the output of this system $y(t)$ is composed of the following two parts; the linear component $z(t)$ and non-linear component $n(t)$. The power spectrum of output $P_{yy}(f)$ is expressed by the following equation.

$$P_{yy}(f) = P_{zz}(f) + P_{nn}(f) \quad (3)$$

where, $P_{zz}(f)$ is the power spectrum of linear component and $P_{nn}(f)$ is the power spectrum of non-linear component. In addition, the coherence $\gamma^2(f)$ is defined by the following equation.

$$\gamma^2(f) = P_{zz}(f)/P_{yy}(f) \quad (4)$$

From above two equations, the power spectrum of non-linear component is given as,

$$P_{nn}(f) = \{1 - \gamma^2(f)\} P_{yy}(f) \quad (5)$$

As the integration of power spectrum over the entire frequency range agrees with the mean square value, the mean square value of non-linear component $\bar{n}^2$ is expressed by the following equation.

$$\bar{n}^2 = \int_{-\infty}^{+\infty} \{1 - \gamma^2(f)\} P_{yy}(f) df \quad (6)$$

The non-linear components calculated from above equation are shown in Table 5. These results are expressed in terms of standard deviation and coefficients of variation, and the outputs at each condition are L_i , P_i , and P_{max} respectively.

As for Q_f and L_i , the non-linear component at driven rack condition of 17.5 is seemingly large compared with others. The reason is likely to be that, owing to the given variation of a rack, the power spectrum concentrates at lower frequency level, where coherence is especially weak. Except this test condition, the non-linear components in the output of L_i are about 0.0035 mm ms in standard deviation and about 1.5% in coefficient of variation. As both input and output involve the instrumentation error of 0.5% in coefficient of variation, the ideal non-linear component when the instrumentation causes no error is considered to be smaller than the value in Table 6. As the non-linear component is approximately constant, the ratio of the linear component to the whole output as well as the cross-correlation coefficient increases with an increasing cycle variation. Since the cross-correlation coefficient varies according to the amount of cycle variation, the correlation cannot be accu-

ately estimated from the cross-correlation coefficient only.

As for L_i and P_i , the non-linear component at driven rack condition of 17.5 is larger for the same reason as in the case of Q_f and L_i above mentioned. The non-linear component at fixed rack position of 17.5 is not so large with a measurement accuracy of 0.024 Kg/cm². As the input L_i involves a non-linear component in itself, the cycle variation of P_i is rather considered to be very small when the amount of injected fuel of each cycle does not

Table 4 Calculated results for P_{max}

rack position	L_i			P_{max}			ρ
	μ mm ms	σ mm ms	σ/μ %	μ Kg/cm ²	σ Kg/cm ²	σ/μ %	
fixed rack	17.5	0.157	0.002 78	1.64	70.8	1.55	0.135
	19.5	0.265	0.007 35	2.77	72.5	1.51	0.153
driven rack	17.5	0.163	0.009 42	5.78	70.0	1.77	0.352
	19.5	0.231	0.0169	7.34	71.9	1.90	0.119

rack position	P_i			P_{max}			ρ
	μ Kg/cm ²	σ Kg/cm ²	σ/μ %	μ Kg/cm ²	σ Kg/cm ²	σ/μ %	
fixed rack	17.5	2.77	0.062 0	2.24	70.3	1.68	0.225
	18.5	3.38	0.098 4	2.91	71.0	1.64	0.221
	19.5	4.10	0.196	4.78	71.5	2.04	0.449
driven rack	17.5	2.63	0.198	7.51	70.0	1.89	0.334
	18.5	3.29	0.254	7.72	71.8	1.91	0.374
	19.5	4.40	0.239	5.44	72.3	1.88	0.340

Fig.13 Power spectra and coherence function for P_{max}

Table 5 Calculated results of non-linear component

output	$Q_f - L_i$		$L_i - P_i$		$L_i - P_{max}$	
	L_i		P_i		P_{max}	
rack position	σ mm ms	σ/μ %	σ Kg/cm ²	σ/μ %	σ Kg/cm ²	σ/μ %
fixed rack	17.5	0.003 1	1.6	0.038	1.6	1.50
	19.5	0.003 6	1.4	0.126	2.9	1.43
driven rack	17.5	0.004 8	2.5	0.060	2.1	1.89
	19.5	0.003 0	1.1	0.136	3.1	1.63

fluctuate. The evident increase of non-linear component of P_i at the rack of 19.5 may be caused by the non-linearity as shown in Fig.10 or by the other unknown factors besides Q_f .

The non-linear components of P_{max} are significantly large considering its measurement accuracy being 0.4%. In this case, non-linearity of input is considered negligible because low correlation exists between P_{max} and L_i . Therefore, it is concluded that the cycle variation of P_{max} is caused by the other factors than the amount of injected fuel, and its value is 1.5 Kg/cm² in the standard deviation, and 2% in coefficient of variation.

6. Summary

The measurement system adopted in this study, including the method to obtain the values such as indicated mean effective pressure etc. using analog computing circuits, is proved to be accurate enough and useful to investigate the cycle-by-cycle variation.

It was applied to a two-stroke, pre-combustion type diesel engine running at constant speed to investigate these cycle variations, where four parameters such as indicated mean effective pressure, amount of injected fuel and others were measured, and the acquired data of successive 1000 cycles were analyzed satisfactorily.

As to the results of measurement, the following conclusions are obtained:

(1) A linear relation exists between the amount of injected fuel and integrated value of injection nozzle lift. Therefore, the amount of injected fuel can be estimated from the integrated value of injection nozzle lift, and its accuracy becomes better with an increasing cycle variation.

(2) Indicated mean effective pressure and integrated value of injection nozzle lift have a very close inter-relationship between them except in the neigh-

bourhood of smoke limit. The main factor causing the cycle variation of indicated mean effective pressure is the cycle variation of the amount of injected fuel, and the effect of other factors on cycle variation is less than 0.04 Kg/cm² in standard deviation.

(3) The cycle variation of maximum cylinder pressure caused by the cycle variation of the amount of injected fuel is small. The cycle variation of maximum cylinder pressure which is caused by other factors than the amount of injected fuel is about 2%, and this cycle variation is considered to have little effect on cycle variation of indicated mean effective pressure.

It is also proved that the statistical analysis technique with power spectra and coherence function is also very useful for the quantitative and qualitative investigation of the relationship between fluctuational phenomena of an internal combustion engine.

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