

Verification of Equivalent Indicated Mean Effective Pressure Measurement Method

Keiichi NAGASHIMA*
Naoki HANADA*

Keiji MIURA*
Yoshito TSUKAMOTO*

Masahiko MATSUMOTO*
Kazuo TSUCHIYA**

ABSTRACT

Indicated mean effective pressure (IMEP) is generally used as a parameter directly expressing the status of combustion in an internal combustion engine. Issues of data stability, cost, and lifespan, among others, have made the use of pressure transducers in vehicle control applications challenging. The use of a method in which changes in engine vibration and bolt tightening force originating in the pressure diagram are measured and used to monitor equivalent IMEP, which has a strong correlation with IMEP, has potential for the future.

The research discussed in this paper studied a method in which signals originating in the pressure diagram were measured using a piezoelectric ignition plug washer-type force sensor and the results were used in the calculation of equivalent IMEP. When measurements were conducted in an actual engine, a correlation coefficient of 0.799 was obtained between IMEP, as determined from the pressure diagram, and equivalent IMEP, as determined using the force sensor. Alteration of the charge amplifier settings and the setting of a computation gate increased the correlation between equivalent IMEP and IMEP, raising the correlation coefficient to 0.990.

1. Introduction

Measures to reduce pollution and increase fuel efficiency in response to air pollution and climate change on a global scale have become an urgent responsibility in the automotive field⁽¹⁾. In order to satisfy these demands, direct injection gasoline engines have been developed and research is being conducted on homogeneous charge compression ignition (HCCI) engines in attempts to achieve increased thermal efficiency. The variable mechanisms seen in recent valve systems are also playing an important role in increasing fuel efficiency and reducing emissions. On the negative side, the number of control parameters is increasing, and high-volume control data in the form of maps is becoming necessary. In addition, supporting the optimal control for transient operation that is being considered for introduction using conventional map and table reading and interpolation methods⁽²⁾ will be challenging.

Understanding the status of combustion is an important consideration for the development of these types of

engines and the use of these control systems, and the measurement of pressure diagrams has conventionally been employed as the standard method of doing so. Pressure diagrams represent important data, given that the maximum in-cylinder pressure, amount of heat release, and IMEP, which directly expresses volume of work for each cycle, can be derived from them. Moreover, measurements of transient states in actual vehicles are also important for parameter setting for the abovementioned control data and for control. In these cases, data stability in long-term measurements is prioritized even if a certain amount of distortion occurs in the pressure diagram, and the setting of the time constant of the measurement system is an important factor.

Compared to the conventional numerical integration method, the IMEP calculation method proposed by Tsuchiya et al.⁽³⁾ offers a lower rate of calculation error, a higher calculation speed, and makes it possible to conduct calculations using only low-frequency data, even when less data is sampled per cycle.

* Automobile R&D Center

** Meiji University

Using this method, effective utilization of the measurement system can be expected even when there are restrictions upon it. In addition, if the frequency characteristic of the measurement system is known, correction is a simple matter⁽²⁾, and the necessity of applying a frequency characteristic to the measurement system and determining the natural frequency of the sensors themselves is alleviated.

However, the high-accuracy pressure transducers used in engine development are expensive and present issues in terms of sensor life and mounting in the combustion chamber, and modifications are necessary for their use either in vehicle tests or in future engine control systems.

Rather than using pressure transducers that present issues of cost and life in addition to restrictions on layout, the project discussed in this paper used a method of measuring equivalent IMEP, which is strongly correlated with aforementioned IMEP as determined by an expression, from pressure diagram-related signals obtained from a piezoelectric ignition plug washer-type force sensor that can be positioned without any necessity for vehicle modification. This method displayed good results in actual engine tests.

2. Expression for IMEP and Concept of Equivalent IMEP

2.1. Method of Calculating IMEP using Pressure Diagrams based on Expanded Fourier Series

IMEP is generally defined using Eq. (1), based on stroke volume, V_s , in-cylinder pressure, P , and combustion chamber volume change, dV .

$$IMEP = \frac{1}{V_s} \oint P dV \quad (1)$$

If the periodicity of the in-cylinder pressure and the combustion chamber volume change is focused on and they are each expressed as the sum of periodic functions of the Fourier series type, expanded, and organized, Eq. (2) is obtained.

In this paper, the method of calculating IMEP shown as Eq. (2) will be termed “this equation.” Here, the frequency component identical to the angular speed of the engine is treated as the fundamental harmonic.

$$\{IMEP\}_f = \frac{\pi}{2h} \{C_1 \cos \phi_1 + KC_2 \cos \phi_2\} \quad (2)$$

However, $K = (1 + 1/4\lambda^2)/2\lambda$

$\{IMEP\}_f$: IMEP as determined using this equation

C_1, C_2 : Amplitude of 1st- and 2nd-order frequency components

ϕ_1, ϕ_2 : Phase of 1st- and 2nd-order frequency components

λ : Conrod length / Crank radius

h : Constant (2 cycle: 1; 4 cycle: 1/2)

Equation (2) indicates that IMEP is determined exclusively by the 1st- and 2nd-order frequency components in the pressure diagram.

2.2. Concept of Measurement of Equivalent IMEP

Because the pressure transducers used in the measurement of in-cylinder pressure are directly positioned in the combustion chamber, their diaphragms are exposed to high-temperature gases, generating issues of durability and output voltage drift. A method of employing sensors outside the combustion chamber to measure signals expressing changes in the bolt tightening force and acceleration originating in combustion in the cylinders, and using Eq. (2) to determine the equivalent IMEP, which is strongly correlated with IMEP, would therefore be an effective measure^{(4), (5)}. There is no negative effect if the high-frequency components of the signals being detected are damped while they are being transmitted in the combustion chamber, and a sensor optimized for low frequencies can be employed. The research discussed in this paper employed a piezoelectric ignition plug washer-type force sensor (“test sensor” below), positioned directly above the combustion chamber. This layout necessitated no modification of the engine.

3. Calibration of Test Sensor

3.1. Calibration Device

Hydraulic dead weight calibration systems are generally employed in the calibration of pressure sensors, but because the DC component cannot be detected in the case of piezoelectric sensors, a drift occurs in relation to gradual pressure changes, and calibration at a steady pressure therefore represents a challenge. A dynamic calibration system⁽⁶⁾ was therefore used in the present research. Figure 1 shows the overall configuration of this system, and Fig. 2 shows the pressure transfer device. This device moves the pistons, and alternately impresses and releases a calibration pressure from a pressure tank. The maximum impressed pressure is 980 kPa, and the maximum

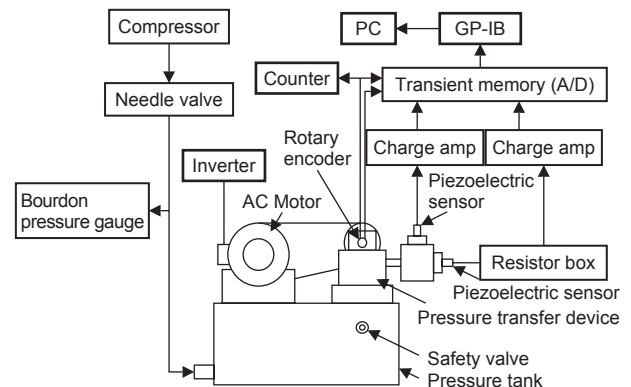


Fig. 1 Dynamic calibration system

impressed pressure frequency is 50 Hz. A combination of the 7061B piezoelectric pressure transducer and 5010 charge amplifier manufactured by Kistler was used as the reference transducer. LONG mode was employed for the time constant.

3.2. Measurement System employing Test Sensor

Figure 3 shows the measurement system, comprising the test sensor, charge amplifier, and cables. This system incorporates a feedback capacity C_f necessary for the conversion of the electric charge Q into output voltage and a feedback resistance R_f necessary for control of the output voltage drift.

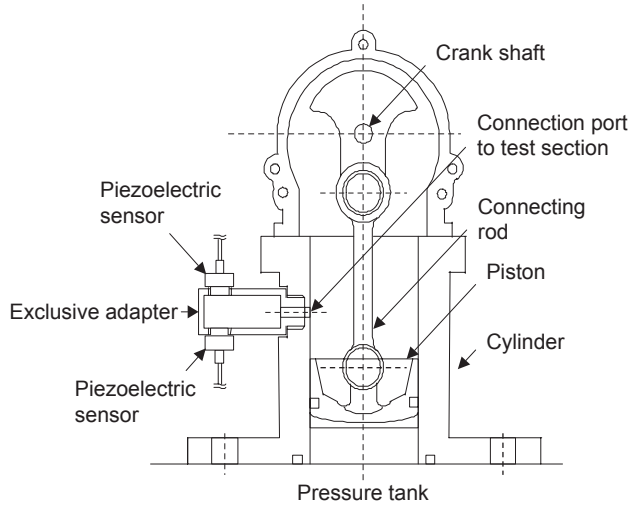


Fig. 2 Pressure transfer device

C_0 : Capacitance of piezoelectric element C_c : Capacitance of cable
 R_{oc} : Sum of piezoelectric element insulation resistance and cable insulation resistance
 C_f : Feedback capacitance R_f : Feedback resistance
 E_i : Input voltage E_o : Output voltage
 Z_i : Input impedance of operational amplifier I_i : Total current
 I_0, I_1, I_2 : Branch current Q : Generated electric charge

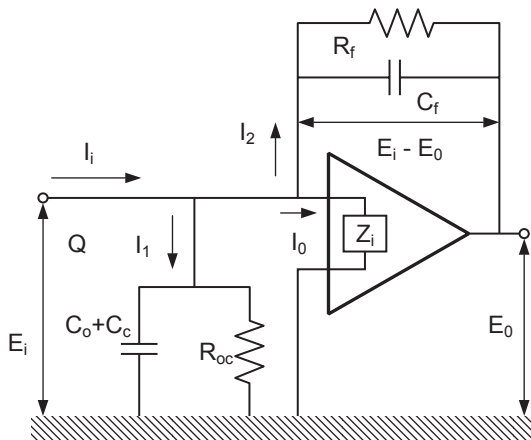


Fig. 3 Measurement system

3.3. Method of Calculation of Sensitivity

The sensor was calibrated with charge amplifier settings of $C_f=1000$ pF and $R_f=10^9 \Omega$ (time constant $\tau = 1$ sec), at a calibration pressure of 400 kPa and an impressed frequency of 10 Hz from the dynamic calibration system. Figure 4 shows the results of measurement of the output waveform for crank angle increments of 0.5 deg and the application of averaging processing to 50 cycles. This graph shows that a voltage drop known as sag occurs in the output waveform, and the output voltage declines with the elapse of time.

If sag occurs in the output waveform, it becomes unclear which output voltage corresponds to the calibration pressure at a given crank angle, making it challenging to employ the conventional method of determining sensitivity from the amplitude of the output waveform in relation to the calibration pressure. In the present project, sensitivity was therefore determined from Fig. 5, showing the output voltage of the reference transducer on the horizontal axis, and the output voltage of the test sensor on the vertical axis. The gradient of the line shows the sensitivity of the test sensor, and y_1 corresponds to the drop in output voltage due to sag. Below, this method will be termed the slope method.

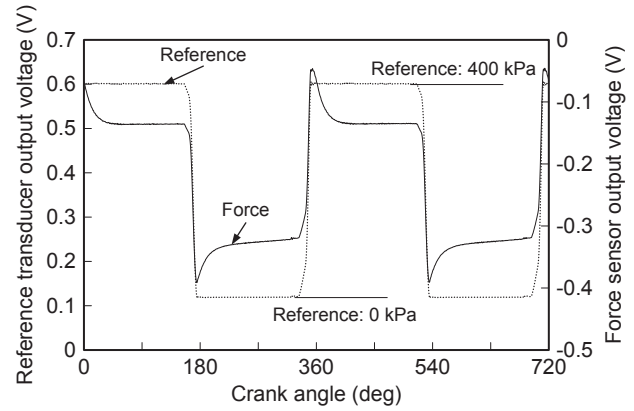


Fig. 4 Results of calibration

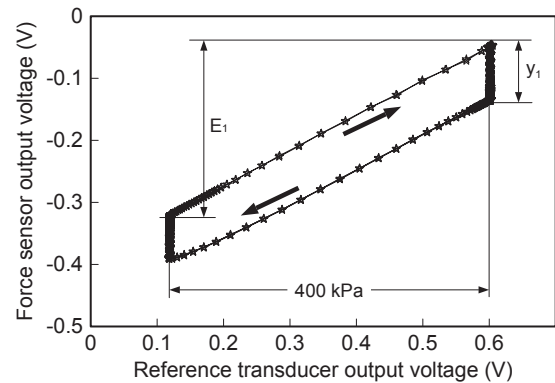


Fig. 5 Calculation of sensor sensitivity using slope method

Table 1 Sensor sensitivity

Calibration pressure (kPa)	Sensitivity (kPa/V)
100	1721
200	1751
300	1864
400	1842
500	1849

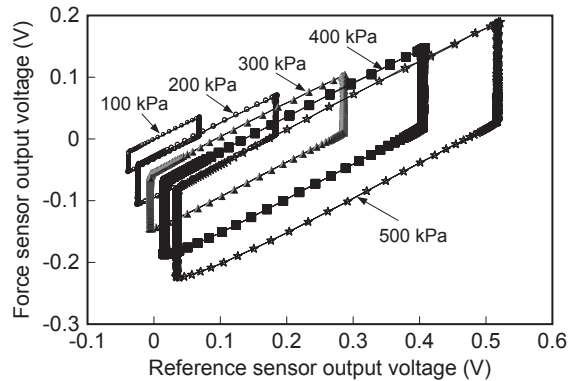


Fig. 6 Result of calibration using slope method

3.4. Calibration using the Slope Method

Figure 6 shows the results of calibration for each 100 kPa increment of impressed pressure from 100 kPa to 500 kPa, at charge amplifier settings of $C_f=1000$ pF and $R_f=10^8 \Omega$ (time constant $\tau = 100$ msec) and an impressed frequency of 10 Hz. Table 1 shows the sensitivity for each increment of impressed pressure, giving an average sensitivity of 1805 kPa/V.

4. Natural Frequency of Test Sensor

In order to accurately determine equivalent IMEP, it is important that the sensor employed should not possess a natural frequency close to the 1st- and 2nd-order frequency components of engine speed. The maximum engine speed of a mass production vehicle is approximately 8000 rpm, while that of a racing vehicle is approximately 20000 rpm. The respective 2nd-order frequency components of these engine speeds is 266.7 and 666.7 Hz. The natural frequency of the sensor should therefore be below this frequency band.

In order to measure the natural frequency of the test sensor when attached in its measurement position, a test sensor and an acceleration sensor were attached to a cylinder head, and a steel ball impact test was conducted. Figure 7 shows the test device. Steel balls of 0.48 mm in diameter and 0.48 g in mass were rolled down a guide secured on a stand and dropped to impact close to the central electrode of the spark plug to which the test sensor was attached. The vibration resulting from the impact was

measured by the test sensor and the acceleration sensor, and a frequency analysis was conducted using an FFT analyzer. The acceleration sensor was attached at the point shown as A in Fig. 8.

Figures 9 and 10 respectively show the output waveform and power spectrum for the acceleration sensor. The results show that the test sensor attached in the measurement position does not possess any natural frequencies within the frequency band that would affect IMEP measurements.

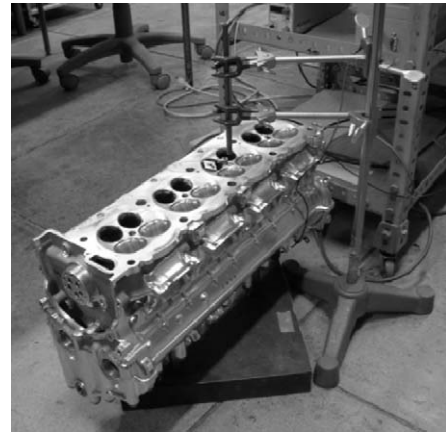


Fig. 7 Steel ball impact test

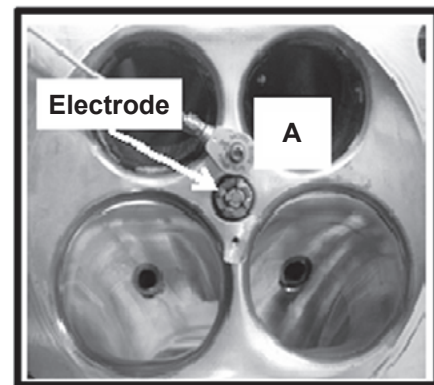


Fig. 8 Location of sensors

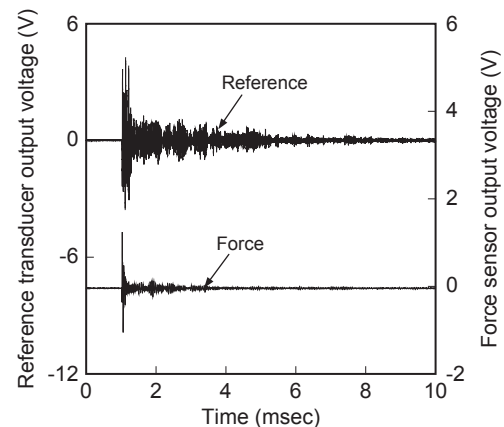


Fig. 9 Sensor output voltage

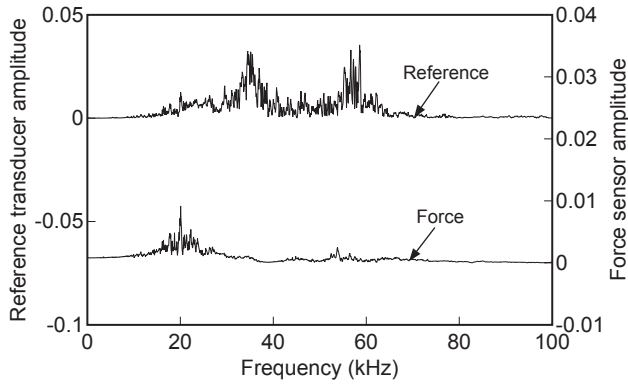


Fig. 10 Power spectrum

5. Measurement of Equivalent IMEP in an Actual Engine

5.1. Test Equipment and Test Engine

Figure 11 shows the test equipments. A test sensor and a pressure transducer to provide data for comparison were positioned as shown in the figure. The output waveforms of the sensors were sent to a Fourier series type combustion analyzer⁽⁷⁾, and sensor outputs in the same cycles were compared. A Kistler 7061B pressure transducer was employed. The transducer was connected to a 5011B charge amplifier, and the time constant was MEDIUM. (This pressure transducer will be termed the “reference transducer” below.) The test engine spark plugs rather than the test sensor were used to provide the spark. Table 2 shows the specifications of the engine used in the tests and the test conditions.

5.2. Results of Measurement of Equivalent IMEP

The system shown in Fig. 3 was used in these tests as the measurement system incorporating the test sensor. C_f was 1000 pF and R_f was $10^9 \Omega$, corresponding to the SHORT mode of pressure diagram measurements. At this time, the time constant τ was 1 sec and the low-range cutoff frequency, f_c , was 0.159 Hz.

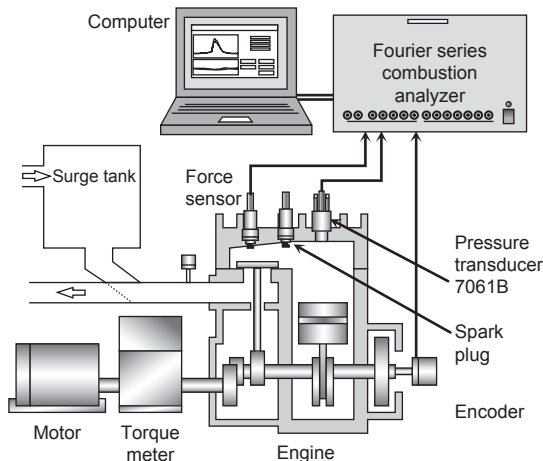


Fig. 11 Test equipments

Table 2 Engine specifications and test conditions

Engine type	Shibaura GEF30RE
Bore × Stroke	78 × 62 (mm)
Displacement	296 (cm ³)
Compression ratio	7.4
Engine speed	1,800 (rpm)
Throttle	1/4 - 3/4
Ignition timing	BTDC 22 (deg)
A/F	12.7, 15.3

The output waveforms of the test sensor and the reference transducer were recorded for 300 cycles under the conditions shown in Table 2 (A/F=12.7), and then averaged. The results are shown in Fig. 12. These results indicate that except for the high harmonic noise component of the output waveform of the pressure transducer, its form is close to that of the pressure diagram. Figure 13 shows the changes in IMEP and equivalent IMEP over a continuous 300 cycles. The equivalent IMEP almost exactly traces IMEP.

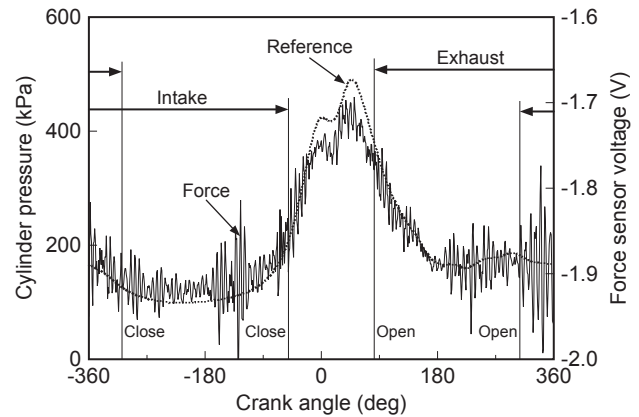


Fig. 12 Cylinder pressure and force sensor output voltage waveforms

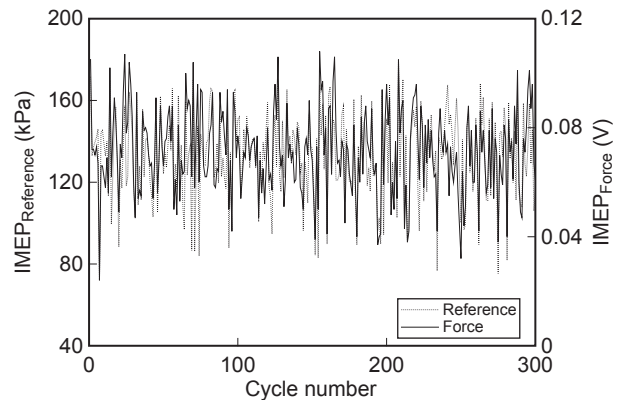


Fig. 13 IMEP and equivalent IMEP in continuous cycles

Figure 14 shows the correlation between the equivalent IMEP and IMEP. The correlation coefficient was 0.799.

The results discussed above indicate that rough monitoring of IMEP is possible under the test and measurement conditions employed in this research. However, more precise tracing and an increased level of correlation would be necessary for the achievement of more accurate measurements of equivalent IMEP and their application in engine control.

5.3. Achievement of Increased Equivalent IMEP Measurement Accuracy

When measurements are conducted using the combination of a piezoelectric sensor and a charge amplifier, if the insulation electric resistance (R_{oc} in Fig. 3) declines, baseline drift occurs in the output waveform. If this drift continues for an extended period, it eventually exceeds the measurement range, and measurements can no longer be conducted. Decline in the insulation electric resistance results from factors such as infiltration of fluid droplets into the connectors and increases in the temperature of the elements, and to control it, it is necessary to use a low setting for the feedback resistance, R_f . The stability of the baseline was therefore verified at an R_f setting of $10^9 \Omega$, the setting used in the previous sections. The engine described in Table 2 was used as the test engine. 2/4 throttle and an A/F of 12.7 were selected as the test conditions. A pressure diagram was measured using the reference transducer for the purposes of comparison. The results are shown in Fig. 15. As the figure shows, baseline drift occurs in the test sensor output as the engine is operating, and it tends to exceed the measurement range. It was therefore necessary to set R_f at a lower figure. It was possible, however, that employing a lower setting for R_f might reduce the ability to detect low-frequency components, and thus affect measurements of equivalent IMEP. If the frequency characteristic of the measurement system was determined in advance, correction could be applied⁽⁴⁾ as a measure in response to this phenomenon. It was therefore practical to prioritize the achievement of stability by setting R_f at a lower figure.

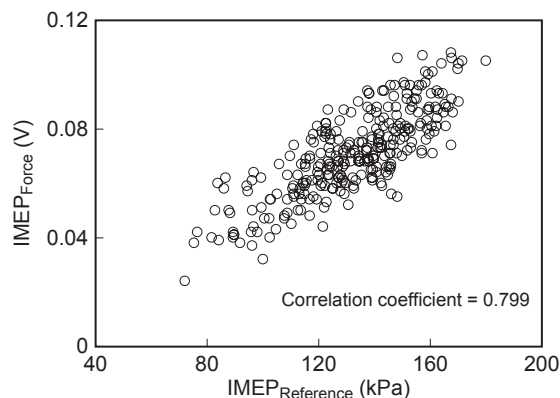


Fig. 14 Relation between IMEP and equivalent IMEP

In addition, electric noise and vibration is superimposed on the test sensor output waveform, as shown in Fig. 12. In this case, the SN ratio declines in the range in which in-cylinder pressure is low, such as the intake and exhaust strokes, and the SN ratio becomes comparatively good when the in-cylinder pressure is high, close to compression top dead center. A computation gate was therefore positioned close to compression top dead of center, where the SN ratio was favorable, and equivalent IMEP was calculated using only the data inside the computation gate.

Figures 16 and 17 show the results obtained when R_f was changed to $10^8 \Omega$ and a computation gate was set at compression top dead of center ± 120 deg in order to test the accuracy of measurements of equivalent IMEP. Figure 16 indicates that equivalent IMEP traces changes in IMEP, while Fig. 17 shows an increase in the correlation coefficient from the figure of 0.799 shown in Fig. 14 to 0.990.

5.4. Application in High-speed Engine

This section will discuss the application of the method to a high-speed engine using the results obtained up to the previous section. A V8 racing engine with a bore of 97 mm, a stroke of 40.25 mm, and a compression ratio of 13.0 was employed. The engine was operated at 14000 rpm at

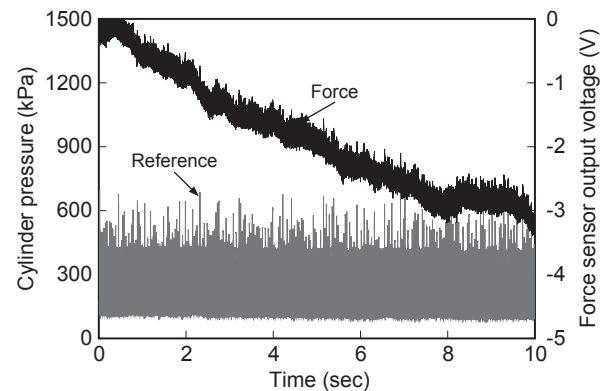


Fig. 15 Baseline drift of sensors

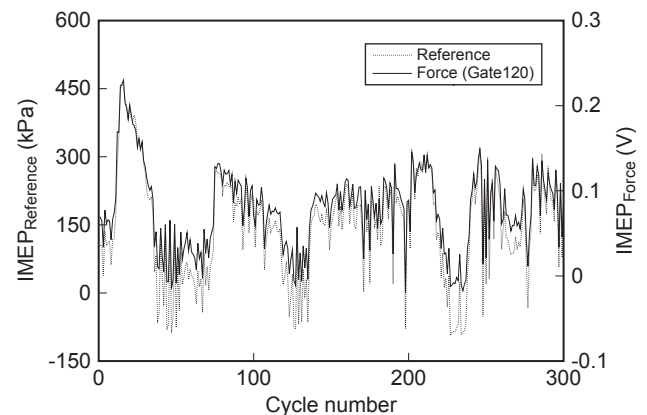


Fig. 16 IMEP and equivalent IMEP in continuous cycles (R_f modified)

wide-open throttle, an A/F of 13.1, and an ignition timing corresponding to MBT. In the case of the measurement system used for detection of equivalent IMEP, a test sensor was positioned in the 7th cylinder, and the feedback resistance of the charge amplifier was set at $R_f=10^8 \Omega$. For purposes of comparison, a pressure diagram was measured simultaneously using a Kistler 6081AQ05 transducer and 5011 charge amplifier (MEDIUM mode was used for the time constant). No gate was set for the data processing.

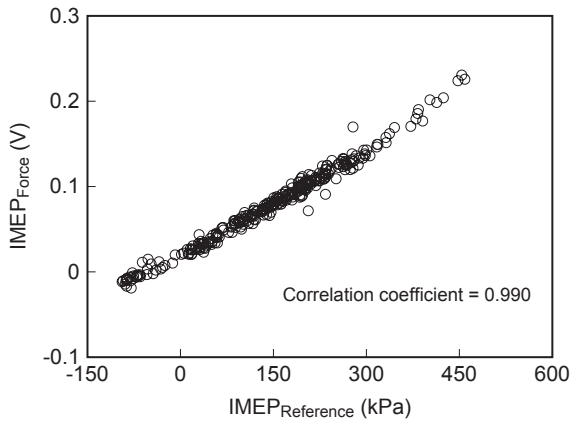


Fig. 17 Relation between IMEP and equivalent IMEP (R_f modified)

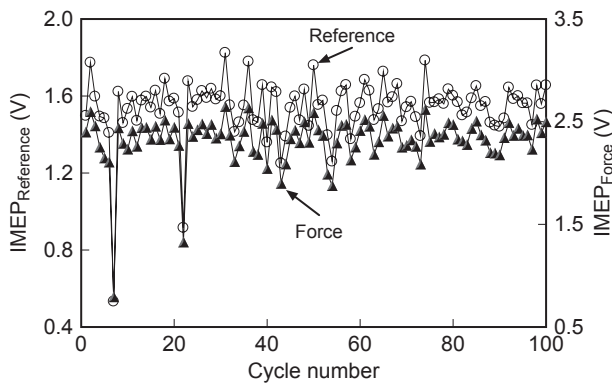


Fig. 18 IMEP and equivalent IMEP in continuous cycles (in high-speed engine)

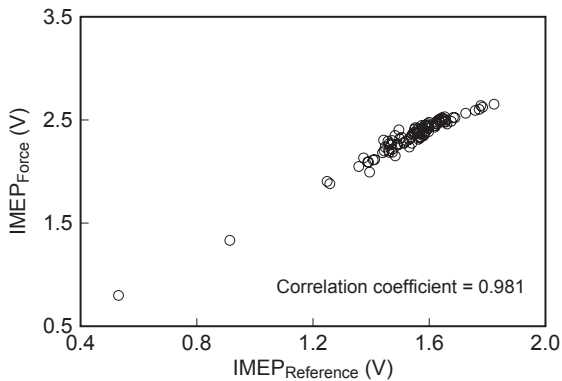


Fig. 19 Relation between IMEP and equivalent IMEP (in high-speed engine)

Figure 18 shows changes in IMEP and equivalent IMEP over 100 cycles, indicating that equivalent IMEP is able to trace changes in IMEP even in a racing engine. Figure 19 shows the correlation between equivalent IMEP and IMEP. A high level of correlation is achieved, with a correlation coefficient of 0.981.

The results above demonstrate that equivalent IMEP can be accurately measured even in a high-speed engine such as a racing engine if the charge amplifier settings are optimized.

6. Conclusions

The use of an ignition plug washer-type force sensor that could be positioned without modification of the engine helped to enable the measurement of equivalent IMEP, a parameter with a strong correlation with IMEP. The results obtained are as follows:

- (1) When measurements of equivalent IMEP were conducted using the ignition plug washer-type force sensor using a setting corresponding to the SHORT mode of the time constant for pressure diagram measurements ($R_f=10^9 \Omega$), a correlation coefficient of 0.799 was obtained between equivalent IMEP and IMEP. This correlation was adequate for rough monitoring, but the achievement of increased ability to trace IMEP and a higher level of correlation were necessary for use of the method in applications such as engine control.
- (2) The use of an R_f setting of $10^8 \Omega$ and the setting of a computation gate at ± 120 deg in order to use only data close to compression top dead center in the calculation of equivalent IMEP increased the ability of equivalent IMEP to trace IMEP and increased correlation to 0.990.
- (3) The correlation between equivalent IMEP and IMEP could be increased even in a racing engine operated at high engine speeds by optimization of the charge amplifier settings.

References

- (1) Daisho, Y.: A Prospect on Automobiles for the 21st Century -Resolving Problems Associated with Environment and Energy-, Journal of JSAE, Vol. 56, No. 1, p. 18-24 (2002)
- (2) Tsuchiya, K.: Applications of Indicated Mean Effective Pressure to Engine Control, Journal of JSAE, Vol. 58, No. 4, p. 25-30 (2004)
- (3) Tsuchiya, K., Nagashima, K.: A Calculation Method for Indicated Mean Effective Pressure Based on Harmonic Analysis of Pressure Waveform, International Journal of Engine Research (JER03702), Vol. 4, No. 2, June (2003)
- (4) Tsuchiya, K., Kouchi, Y., Miyamoto, T.: Monitoring Method of Indicated Mean Effective Pressure by Use of Acceleration, Force and Gap Sensors, JSAE Annual Congress Proceedings, 28-06, p. 5-8 (2006)

- (5) Nishio, S., Tsukahara, S., Tsuchiya, K., Sakai, M.: Development of Marine Diesel Engine Management System (2nd Report), 76th, JIME Annual Congress Proceedings, A109 (2007)
- (6) Kawa, T., Miura, K., Hatano, Y., Minagawa, T., Kawa, H., Yanagihara, S.: Development of Dynamic Calibration Systems for Cylinder Pressure Sensors, JSAE Annual Congress Proceedings, 14-07, p. 1-4 (2007)
- (7) Nagashima, K., Tsuchiya, K., Kamimoto, T.: Development of Fourier Series Type Combustion Analyzing System, JSAE Transactions, Vol. 33, No. 2, p. 31-36 (2002)

■ Author ■



Keiichi NAGASHIMA



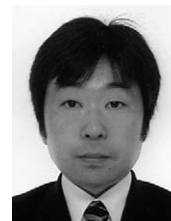
Keiji MIURA



Masahiko MATSUMOTO



Naoki HANADA



Yoshito TSUKAMOTO



Kazuo TSUCHIYA