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A Study on the Monitoring System for Engine Control by Measuring Combustion Pressure Continuously in All Cylinders

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Abstract : A marine diesel engine should realize optimal operation efficiency while reducing NOx, PM (Particulate Matters) and other emissions. Fuel injection systems that use electronic control can become an effective means of achieving that objective. However, it still needs some accurate and instant information in order to bring its ability into full potential while sailing on the sea. The important information of them are a shaft torque and continuous combustion pressures of all cylinders.

The shaft torque and the propeller thrust described in this paper are measured at an intermediate shaft by using a unique principle that one of two electromagnet coils oscillates a vibrating strip which the length changes with force and the other coil picks up the change of the frequency of the vibrating strip. For further reference, the shaft power meter multiplied the torque bythe shaft revolution has already had about 750 sets of sales performance. The research presented in this paper started about ten years ago and is concerned with the development of a combustion pressure sensor that uses the same principle. Recently, the pressure sensor which bears continuous operation has been developed after a hard struggle, that is, the system that consists of a shaft horsepower meter, a propeller thrust meter and a combustion pressure sensor has been completed and has been shown to be reliable.

This paper describes the configuration of this system, the material of the combustion pressure sensor, the principle of that, and the improving point of the sensor, and, we finally consider the use of this system.

Key words : Diesel engine, Optimal operation, Torque and combustion pressure, Electronic fuel injection pump

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1. Introduction

Up to the present, diesel combustion monitoring systems have been developed by some manufacturers, and sold on the market. However, some of them fail to survive more than a few years because of critical defects. At present, there is still no monitoring system that is universally recognized as being successful.

It can be said simply that the primary problem of existing systems concerns the combustion pressure sensor. There is a demand for a pressure sensor that offers continuous operation and is free from the hindrance of heat, vibration and carbon residuum. Evidence suggests that the existing pressure sensors cannot fill the demand even if the systems are managed by advanced microprocessors or skilled software. However, the diesel engine combustion monitoring system that we have developed contains an efficiently reliable combustion pressure sensor, it also contains a shaft power meter and a propeller thrust meter.

2. System Configuration

The system is shown in Fig. 1. 'The combustion pressure sensor' is explained in more detail in section 3 of this paper.

The local unit contains oscillators, which drive vibrating strips of pressure sensors, and a signal control module, which processes samples and transfers these signals to the control/display unit SE356.

The control/display unit SE356 is a computer unit with a built-in monitor to control data processing and signal transmissions and to display information as numerical data on engine combustion, a pressure/crank-angle diagram, a pressure/volume diagram and others. In addition, this unit can obtain data on shaft torque and propeller thrust by simply using the same principal as a pressure sensor.

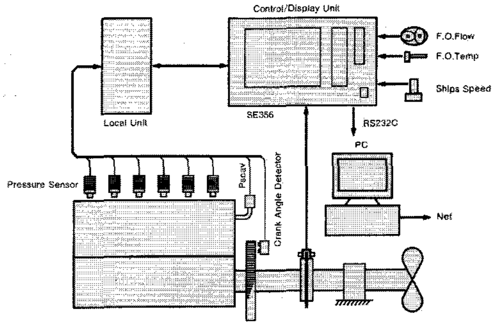

Fig. 1 System configuration

A top dead center signal is generated by a photo sensor which is put close to a metal piece on a flywheel. The pulse signal executes an accurate sampling of combustion pressure in relation to every crank angle.

3. Combustion Pressure Sensor

3.1 Raw Material

The pressure chamber of the combustion pressure sensor is made of a super nickel alloy,which assures static pressure up to 68.6 MPa, has corrosion-resistance up to 816℃ with high creep and rapture strength which allows it to be used for gas turbine and jet engine parts. The sensor performance has been excellent, especially as a spring material for service at temperatures of less than

650℃.

Mechanical characteristics are shown below.

Tensile strength: 1,166 to 1,421 N/mm^2
Yield strength: 823 to 1,127 N/mm^2
Elongation: 15 to 25 %
Hardness (HB): 313 to 400

3.2 Principle of Measurement

The combustion pressure sensor is mounted on the engine indicator valve. The combustion gas is received through the pressure chamber. When combustion pressure P (in Fig. 2) is applied to the chamber, the vibrating strip in the diagram becomes elongated and its tension increases. Coil units consisting of two electromagnet coils are placed closely to the vibrating strip. One of the coils is an exciting coil that oscillates the vibrating strip continuously, and the other picks up the signal frequency.

The length and circumference of the pressure chamber are extended by combustion pressure but their resilient nature allows them to return to their original dimensions. Accordingly, the length L in Fig. 2 is directly proportional to pressure P.

A vibrating strip is stretched on the pressure chamber at a span L. When the vibrating strip is forced to oscillate by the electromagnet coil, it vibrates at its natural frequency f which depends on the tension F of the vibrating strip as shown by equation (1) .

When gas pressure P is induced within the pressure chamber, L will be changed andit will likewise change F and f. This means that the change in f is the change in P. Equation (1) is simplified by squaring both terms.

The calibration constant C (see equation (3)) of every pressure sensor, and the relationship between the change of sensor signal and pressure P is determined individually in unit of MPa/Hz^2.

In practice, because the change of combustion pressure is momentary, the sensor signal f is measured by counting every one signal cycle time T (seconds) and sequentially substituting this into the equation (2) for continuous outputs of pressure variations. The initial frequency of the vibrating strip is set to approximately 2400 Hzin order to obtain fine resolution by narrowing the signal pulse (the torsion and thrust sensor is set to approximately 500 Hz)

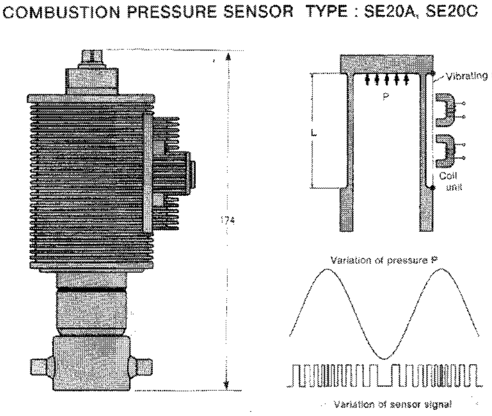

Fig. 2 The principle of sensor

$$f=\frac{1}{2}\sqrt{\frac{F}{\rho}\left(\frac{m^2}{a^2}+\frac{n^2}{b^2}\right)} \qquad (1)$$

$$f=\frac{1}{T} \qquad (2)$$

$$P = Psa + \Delta f^2 \times C \tag{3}$$

Where:

f = Vibrating frequency (Hz)
F = Tension of vibrating strip
ρ = Density of vibrating strip
m, n = Integers
a, b = Length & width of strip
T=One cycle time of sensor signal (sec)
P = Pressure (MPa)
Psa = Scavenging air pressure (MPa)
C = Calibration constant of sensor

Due to the fact that the pressure chamber has the same coefficient of liner expansion as the vibrating strip, the sensor signals remain unchanged if both have the same temperature variation. However, in order to avoid an error that a slight deviation creates, an auto zero scanning function sets the lowest pressure in one cycle to boost air pressure.

3.3 Sensor Improvement

The history of research and development of the sensor is, so to speak, a history to prove it to bear continuous duty.

During the first two years of this research, much effort was spent trying to overcome the problems of high temperature in use. Burnout of the exciting coil that oscillates the vibrating strip and breaking down of the coil were continuous problems. These problems were solved by improving the cooling fin form of the housing and by using thicker windings.

The next problem was data change due to influence of vibration from the engine itself. The cause of the problem was due ot the vibrating strip which was forcibly swayed by vibrationsfrom the sensor attachment part. The lower part of sensor was modified to damper the structure and this problem was solved.

In prolonged use, the inside of the sensor becameblocked with carbon. It did not however occur in the case of 'A' heavy oil use but only occurred in the case of 'C' heavy oil use. Lastly, modification of an internal structure and installing the blow-off valve shown in Fig. 3 were solutions to the troubles.

Now, we are improving the software of the system to respond to user's requests.

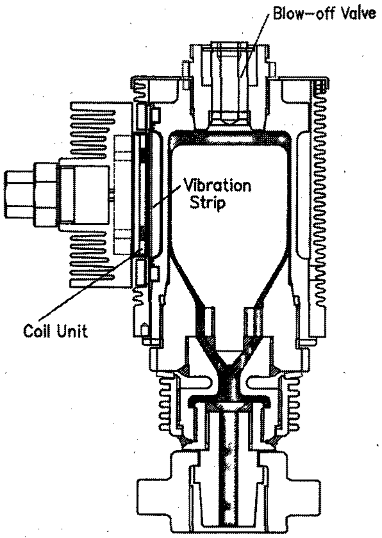

Fig. 3 Pressure sensor with a blow-off valve

4. Use of the System

4.1 Measurement of Mechanical Efficiency and Propeller Efficiency (behind ship)

Although mechanical efficiency is the ratio of brake output obtained at the crankshaft end to indicated output obtained from combustion pressure, this is almost equal to the ratio of shaft output obtained at the intermediate shaft to indicated output. We can guess the grade of frictional wear and the fouling situation of each part of the engine by the efficiency.

Propeller efficiency (behind ship) is the ratio of delivery output to thrust output that is the product multiplied thrust of propeller behind ship by the ship speed to water. This is almost equal to the ratio of shaft output to thrust output. We can estimatethe situation of the hull and propeller by the efficiency.

4.2 Information Sources for Combustion Control

4.2.1 To Arrange the State of Combustion of All Cylinders

Each of Fig. 4 and Fig. 5 is a typical indicator diagram used for operation management of a diesel engine. By overlapping and displaying the graph of all cylinders, as shown in a figure, this graph becomes a good datum to judge whether the state of the combustion of which cylinder is good or not. Comparison will become easier if a part of the graph is enlarged and overlapped as shown in Fig. 6.

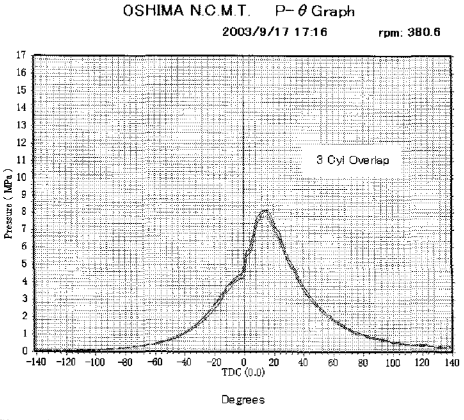

Fig. 4 Pressure and crank angle (3 cyl. overlap)

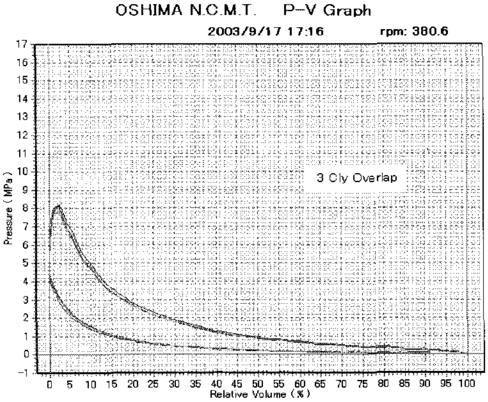

Fig. 5 Pressure and volume (3 cyl. overlap)

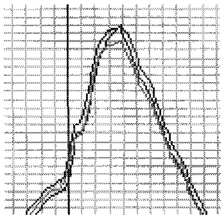

Fig. 6 Partial enlarged graph

4.2.2 To Control the Rapid Increase of Torque

Each of Fig. 7 and Fig. 8 shows correlation between the torque τ with the maximum pressure Pmax in a cylinder or between τ and the exhaust gas temperature Tex. The results are obtained from the test engine of which the specifications are shown below.

Type: 4-stroke cycle with supercharger
No. of cylinder: 3
Cylinder bore: 230 mm
Maximum continuous output: 257 kW
Maximum continuous speed: 420 rpm
Piston stroke: 330 mm

The figures more clearly show that torque has a close relation to these values with an average correlation coefficient of 0.9980 or 0.9977. The rise of maximum pressure in the cylinder increases friction between parts of the engine and becomes the main factor of engine trouble. The rise of exhaust gas temperature causes not only a decline in efficiency by exhaust loss increase but also the burning of the heat exchangerwhich is called as an exhaust gas boiler or an exhaust gas economizer.

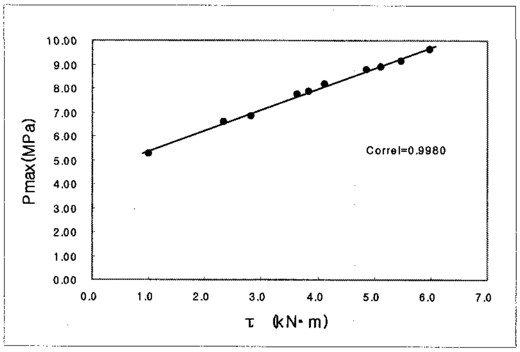

Fig. 7 Torque and maximum pressure

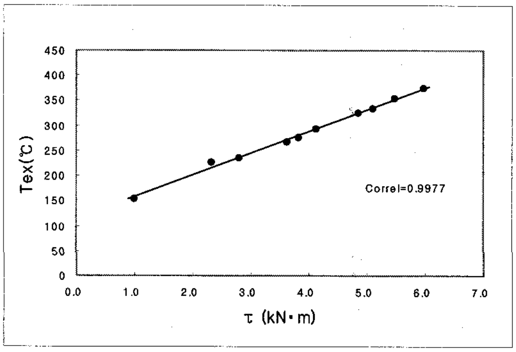

Fig. 8 Torque and exhaust gas temperature

4.2.3 To Avoid the State of Torque Rich

The state at which the torque is larger than the revolution in ratio, so-called torque rich, causes the temperature of each part of the combustion chamber increase. Moreover, even in a low revolution range, the engine performance reaches a smoke limit and discharges much smoke.

The authors advocate Torque Rich Coefficient (TRC) as is expressed with formula (4). As this value gets larger over the limit by the engine manufacturer, the state of the engine getsseverer to the same revolution. Fig. 9 is the case of the engine at torque rich state intentionally. The center line in the figure shows the propeller characteristic. Although the state of the engine under this line is normal, the High TRC line is at the state of heavy torque rich. Fig. 10 shows comparingthe ballast state with full load state of the real ship (27,160kW).

$$\begin{aligned} TRC &= (SHPi/SHPm)/(Ni^3/Nm^3) \\ &= (\tau i/\tau m)/(Ni^2/Nm^2) \end{aligned} \qquad (4)$$

Here is

SHPi: Measured shaft output (kW)

SHPm: Shaft output at the time of rating (kW)

Ni: Measured revolution (rpm)

Nm: Rated revolution (rpm)

τi: Measured torque (kN-m)

τm: Torque at the time of rating (kN-m).

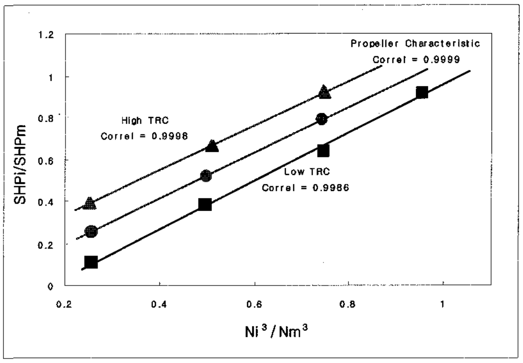

Fig. 9 TRC in test engine

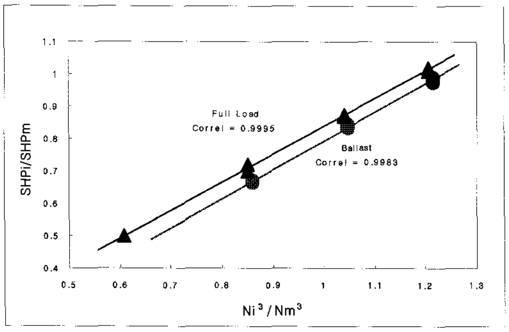

Fig. 10 TRC in real ship (27,160kW)

4.3 Measurement of the Rate of Heat Release[1]-[3]

Recently it is argued that both the combustion temperature and period in a cylinder influences products of combustion, such as NOx, SOx, PM (Particulate Matter) and others. Therefore, the need for a rate of heat release, which shows the process of combustion, is increasing. The authors also add the function of drawing the diagram of the rate of heat release to the system.

A differential heat energy dQ consists of the following equation.

$$dQ = \frac{k}{k-1} pdV + \frac{1}{k-1} Vdp \qquad (5)$$

Where:

k: Specific heat ratio

p: Gas pressure

V: Gas volume

Gas volume V is a function of crank angle θ and is shown as follows.

$$V = \frac{1}{2} \times A \times L \times \left\{(1-\cos\theta) + \frac{1}{4\rho}(1-\cos 2\theta)\right\} + Vc \qquad (6)$$

Where:

A: Piston area

L: Stroke length

$$\rho = \frac{L}{r}$$

r: Crank radius

Vc: Clearance volume

The rate of heat release is

$$\frac{dQ}{d\theta} = \frac{k}{k-1} p \frac{dV}{d\theta} + \frac{1}{k-1} V \frac{dp}{d\theta} \qquad (7)$$

As the diagram drawn by this equation has a lot of noise, it needs filtering noise. Fig. 11 shows the clear diagram for the rate of heat release after filtering.

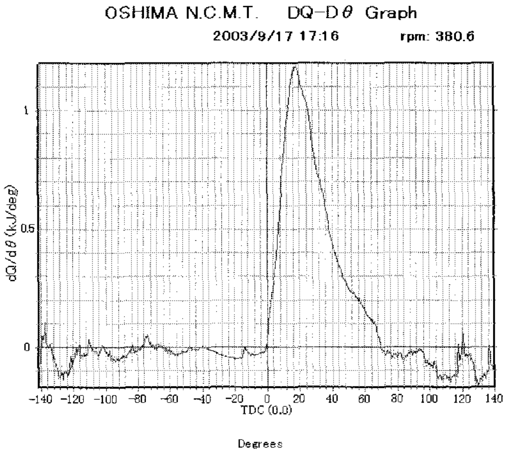

Fig. 11 Rate of heat release

5. Future Combustion Control by using this System

Because a governor adjusts the amount of fuel released into the cylinder after the torque of the intermediate shaft is detected, there is a slight time delay. If the rapid increase of the torque is suppressed during the period, or if the ratio of the torque to a revolution is also stopped in the recommendation range of an engine manufacturer during the period, the optimal control of an engine will be attained.

The diagrams shown in Fig. 12 and Fig. 13 are the examples of injection timing control on an engine of 27,160 kW output. Although the engine load increases from 85% to 100%,the maximum pressure in a cylinder is stopped under about 14 MPa. Accordingly, if the electronic type fuel injection system[4] which is currently being researched and is under development recently is combined with this system and adjust the injection timing of fuel into all cylinders instantly and simultaneously, a more optimal control of the engine will be achieved.

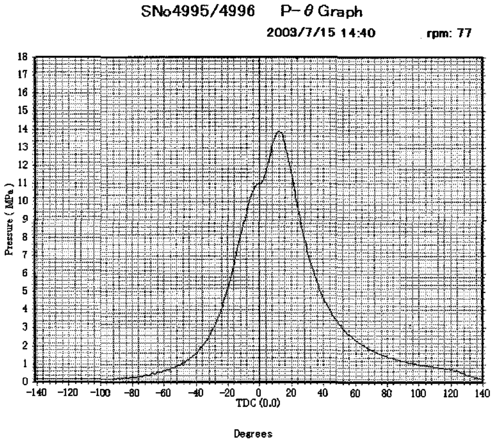

Fig. 12 85% load

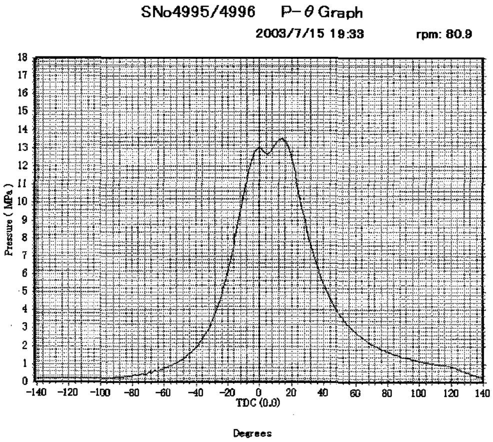

Fig. 13 100% load

6. Conclusion

This system consists of a shaft power meter, a propeller thrust meter and a combustion pressure sensor. The combustion pressure sensor that has been completed after ten years of research is reliable for continuous duty, free from the hindrance of heat, vibration and carbon residuum.

Users can make use of this system as information sources of the following.

(1) The grade of frictional wear and fouling of each part of an engine by mechanical efficiency.

(2) The grade of fouling and other situations of a hull and propeller by propeller efficiency (behind ship).

(3) The combustion process by the rate of heat release.

Users can also perform combustion control for the sake of the following by the use of this system.

(1) To arrange the state of combustion of all cylinders.

(2) To control the rapid increase of torque.

(3) To avoid the state of torque rich.

In the future, if the electronic type fuel injection system which is currently being researched and is under development is combined with this system and is used to adjust the injection timing of fuel into all cylinders instantly and simultaneously, a more optimal control of an engine will be achieved.

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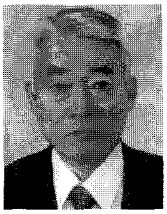

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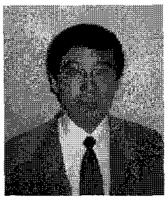

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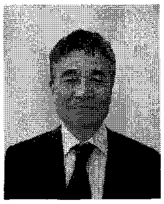

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