

Knocking Quantification and the Development of a Knock Intensity Meter

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ABSTRACT

An algorithm which processes pressure signals in cylinders with a first frequency element and quantifies it based on its maximum value and statistic processing, and a real time measuring system utilizing the algorithm were established. To attain high applicability this system employs not only generally applied pressure sensors but also plug washer type sensors that can be applied to each cylinder for pressure measurements. Further, nearly all of the processing is performed using software applications. Rewriting of the software is made possible due to the simplified operations and the application of a VME board equipped with a high performance MCU processing built-in flash ROM. In consideration of expanded application in the future, the system, further, utilizes a special interface to enable automatic operation with the bench top automatic measuring system.

1. Introduction

Numerous manufacturers, primarily automobile manufacturers, are continually striving to develop revolutionary new technologies for decreasing fuel consumption, including the development of fuel-injected gasoline engines and hybrid automobiles, in an attempt to accommodate the environmental issues that have surfaced over the years. It is also important to decrease fuel consumption and reduce exhaust emissions by improving the basic combustion characteristics in the case of ordinary engine development.

In this race to develop new technology, efforts are also being made to develop complex control systems and high-precision measurement supporting techniques that are different from those in the past. We have developed a system for measuring knocking which is generally considered one of the limiting factors for improving the combustion characteristics of an internal combustion engine. This new system provides greater measurement accuracy than is possible with conventional methods by applying real-time measurement techniques that make it applicable to automated operation. A description of this new system is reported here.

2. Objectives of Knocking Quantification

The traditional assessment of knocking has relied largely on the sensory perception (hearing and vision) of the person performing the measurement. Errors consequently occur due to variations among individuals performing the measurement, differences among testing laboratories, and differences due to weather conditions. The result is an inadequate level of measurement accuracy.

Knocking has been quantified in the past by using

cylinder pressure sensors, acceleration sensors and other devices, but the complexity of the processing method and the need for a sophisticated CPU with a very large memory have made these methods unsuitable for quantifying and evaluating knocking on a real-time basis. In addition, since the number of parameters that need to be set during the course of engine development is becoming extremely large to match the increasing complexity of engines, testing will have to provide even greater efficiency in the future.

In consideration of these factors, the following four objectives were established for this development:

- 1) A method enabling the quantitative determination of knocking
- 2) Improved precision for knocking measurement
- 3) Hardware allowing the real-time evaluation of knocking
- 4) Automatic operation having an interface with a benchtop automatic measurement system

3. Quantification Method

3.1. Quantification Sensor Selection

It is necessary to select the most suitable sensor as the first step in quantifying knocking. Previous methods, which measured the cylinder pressure directly, used an acceleration sensor and evaluated sound. We evaluated the change in output of each type of sensor in the presence and absence of knocking for various ignition timing settings and analysis frequencies in order to select the most suitable sensor to quantify knocking. Figs.1, 2 and 3 show the results of the frequency analysis. Either of the results is an average of multiple cycles.

Each sensor demonstrated a change in output according to the ignition timing at a frequency of 7-8 kHz corresponding to the main component of knocking. In

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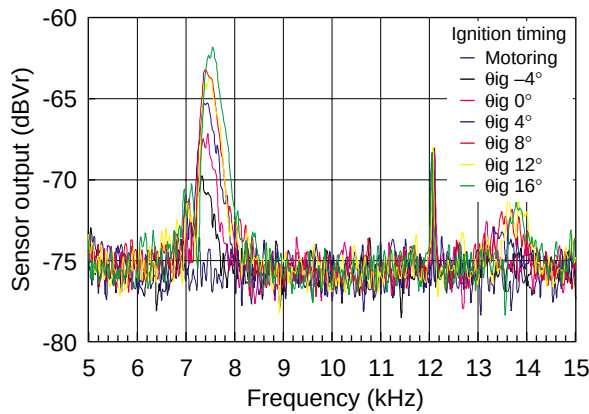


Fig.1 Frequency analysis by cylinder pressure sensor

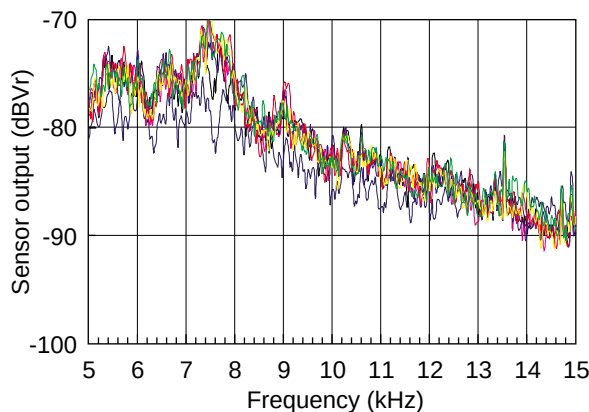


Fig.2 Frequency analysis by air-borne noise

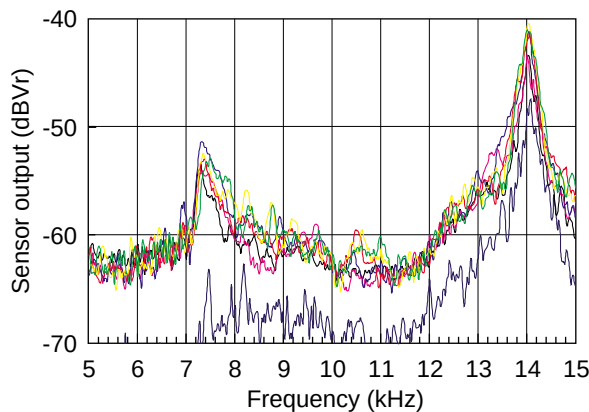


Fig.3 Frequency analysis by plug washer type sensor

addition, a similar change was observed in the frequency range of 13-15 kHz corresponding to the secondary component of knocking. Based on the results of the frequency analysis, attention was focused on the 7-8 kHz band. The results summarizing the maximum values of sensor output relative to the ignition timing are shown in Fig.4.

In the method whereby cylinder pressure is directly measured, as ignition timing advances, so does sensor output. However, the correlation between ignition timing and sensor

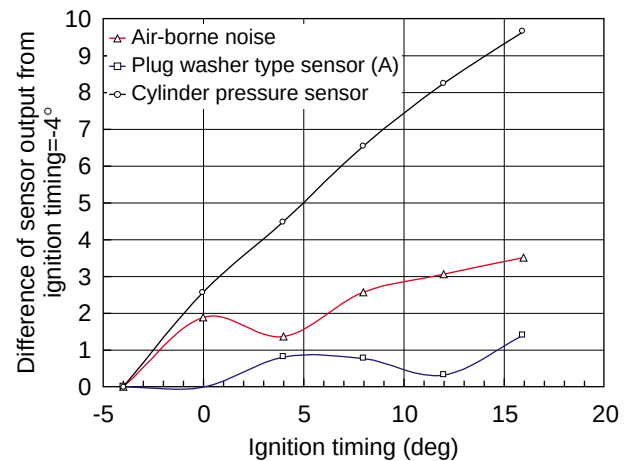


Fig.4 Sensor linearity by ignition timing

output is low with other sensors. In addition, the cylinder pressure sensor can be expected to contribute to improved measurement accuracy due to the large change in output relative to the degree of change in ignition timing. On the basis of these results, the method of directly measuring the pressure was selected for the knocking quantification.

3.2. Quantification Method

Examples of conventional methods that have been reported to quantitatively determine knocking by monitoring the cylinder pressure include one that integrates the heat generation rate and one that integrates this heat generation rate after filtering the cylinder pressure.^{(1)-(3), (5), (6)} However, these methods have the disadvantage of requiring considerable processing time, and from the viewpoint of real-time monitoring, cannot be considered suitable. We therefore decided to employ a method for quantifying knocking that involves filtering the cylinder pressure before statistical processing. Fig.5 shows how this analysis method is applied.

When focusing on the waveform after filtering, examples of the analysis method involve processing the maximum value, the amplitude, and the range between the maximum value and minimum value as shown in Fig.6. When varying ignition timing according to these methods, the output demonstrates a uniform relationship with the ignition timing with both of these methods as shown in Fig.7. Therefore all three methods are able to quantitatively identify knocking.

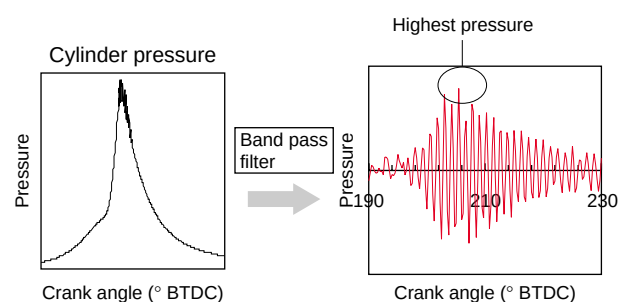


Fig.5 Analysis flow

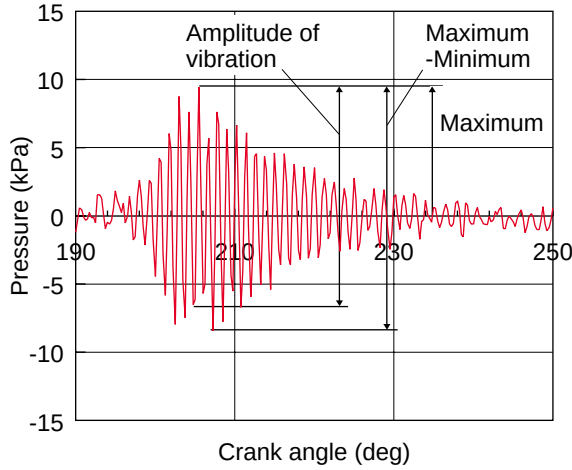


Fig.6 Parameters of knocking identification

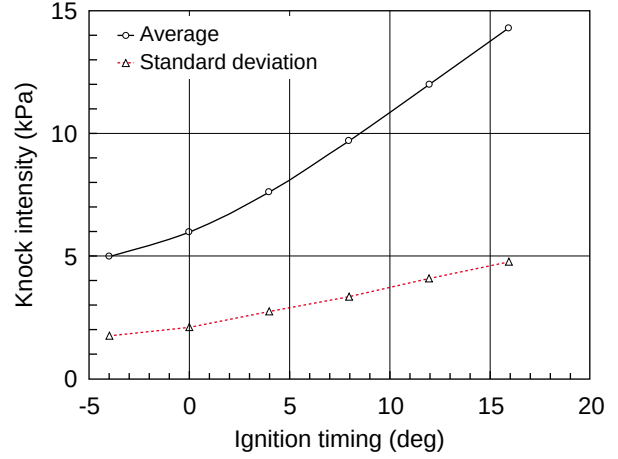


Fig.8 Average standard deviation of knock intensity

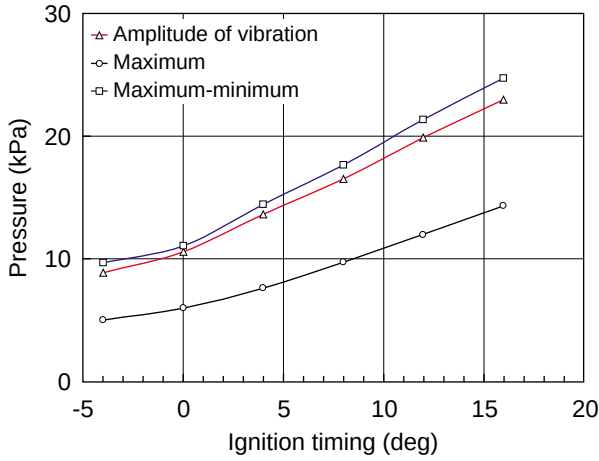


Fig.7 Comparison of analysis methods

We decided to apply the method based on the maximum value output by the cylinder pressure sensor because it requires the simplest processing. Since this maximum value is considered to represent the intensity of knocking, this value is defined as the knocking intensity.

3.3. Knocking Intensity and Frequency

While it is possible for a person to perceive knocking, this perception cannot discriminate between a single heavy knock and a series of continuous mild knocks. It is thus necessary to consider both the intensity and frequency to quantify knocking. Fig.8 shows the average value and standard deviation of the knock intensity according to the degree of ignition advance in the case of sampling 100 cycles. When the ignition timing is advanced, the average value of the knock intensity increases. This means that intense knocking caused by advanced ignition timing is occurring. Similarly, when focusing on the standard deviation of the knock intensity, the value increases with an increasing degree of ignition advance in the same manner as that of the average value.

Fig. 9 indicates the frequency distribution when the knock intensity from Fig.8 is plotted on the horizontal axis. The number of cycles for which the knock intensity exceeds the threshold level increases with increasing ignition advance. This means that the frequency at which knocking occurs (number of cycles) is increasing. On the basis of the foregoing data, knocking can be evaluated by processing the cylinder pressure through a band pass filter and focusing on the maximum value (knock intensity).

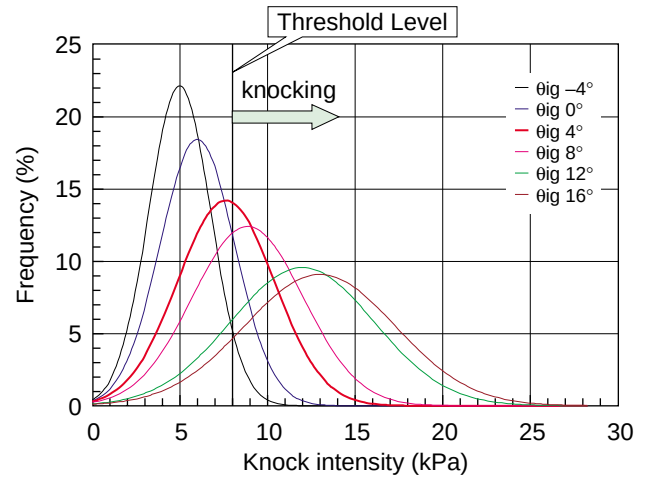


Fig.9 Distribution of knock intensity

3.4. Establishment of the Knocking Threshold Level

Since the conventional evaluation of knocking has been dependent on the sensory perception (hearing and vision) of the tester, it is necessary to maintain a correlation with the conventional method even when applying a new method for evaluating knocking. Fig.10 shows the knocking threshold level for various engine speeds. Although the threshold level rises with increasing engine speed, this is due to the increase in background noise accompanying higher engine speeds as a result of maintaining the correlation with hearing.

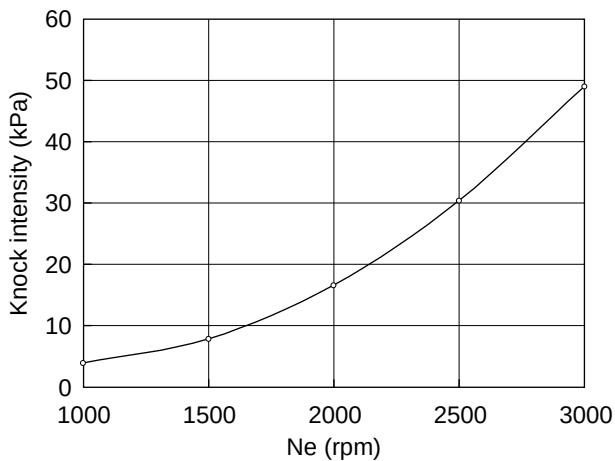


Fig.10 Threshold level table

3.5. Verification of the Quantification Method

The quantification method was verified by quantifying knocking according to the knock intensity as already described. The verification method consisted of changing various parameters, including the engine specifications, type and operating conditions. An example is shown in Fig.11. This method was applied to verify the difference in ignition timing at which knocking occurred when A/F was changed at Ne = 1500 rpm with a wide-open throttle (WOT). Although a difference of 2° occurred due to the difference in A/F at the threshold level as shown in the figure, this coincided with the difference in knocking that was determined by hearing. This quantification method thus demonstrated a high correlation with the conventional evaluation method, and can therefore be used with confidence to evaluate knocking.

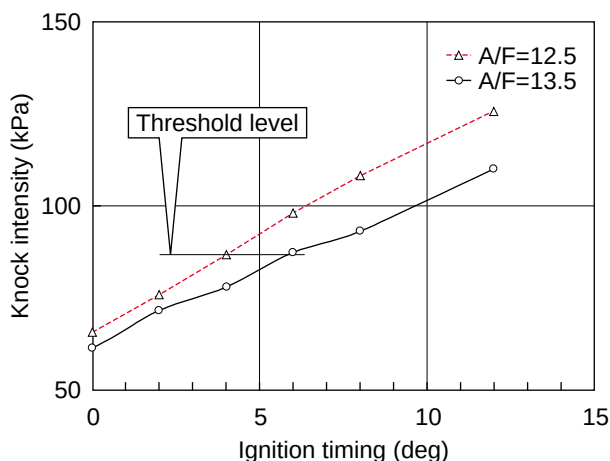


Fig.11 Verification of quantification methods

4. Evaluation of Knocking by a Spark Plug Washer Sensor

It is necessary to install a cylinder pressure sensor in every cylinder in order to perform a simultaneous on-board

evaluation of knocking for all cylinders. However, it is difficult to install a cylinder pressure sensor in every cylinder of a multi-cylinder engine due to the use of multiple valves and the closeness of adjacent cylinders. Therefore, a study was conducted using spark plug washer sensors. This method, however, involves the problem of the change in output according to the ignition timing not being clearly defined due to the poor S/N ratio of this type of sensor, even if the same evaluation method as that used for the cylinder pressure sensor is applied. Therefore, when using spark plug sensors, instead of the averaging multiple cycles, which was performed when using cylinder pressure sensors, individual cycles were examined and the number of cycles for which the knocking intensity exceeded a constant value was counted. The data were evaluated according to that frequency. A comparison between these two methods according to the knock intensity is shown in Fig.12. The evaluation method based on frequency can be seen to give a uniform relationship relative to the ignition timing, thereby allowing knocking to be evaluated.

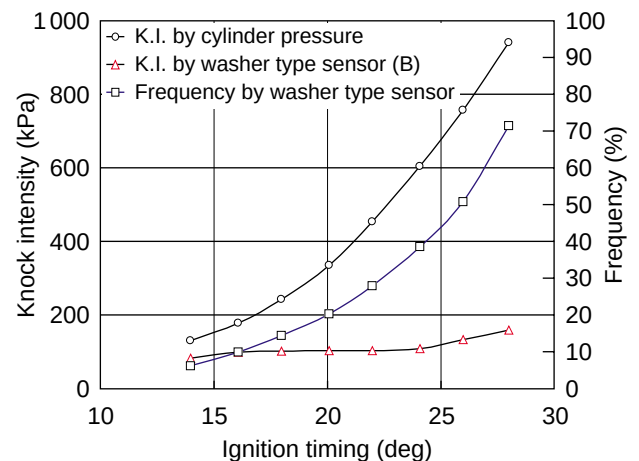


Fig.12 Comparison of quantification methods

5. System Configuration

5.1. Overview

The system block diagram is shown in Fig.13. The majority of the functions required by the system were achieved with suitable software in accordance with the previously stated objectives. In addition, Fig.14 indicates a timing chart for a given cycle starting from the ignition signal and sensor signal through to the determination of measurement timing, band pass filtering and detection of the maximum value (knock intensity).

5.2. Hardware

The basic configuration of the hardware is shown in Fig.15. This system was realized with a VME board containing the functions in the figure in a double-height, 2-slot package. Four of these boards were housed in a VME rack, a single board corresponding to the measurement of one cylinder, so that this system is capable of measuring four cylinders. The appearance of the knock intensity meter is shown in Fig.16.

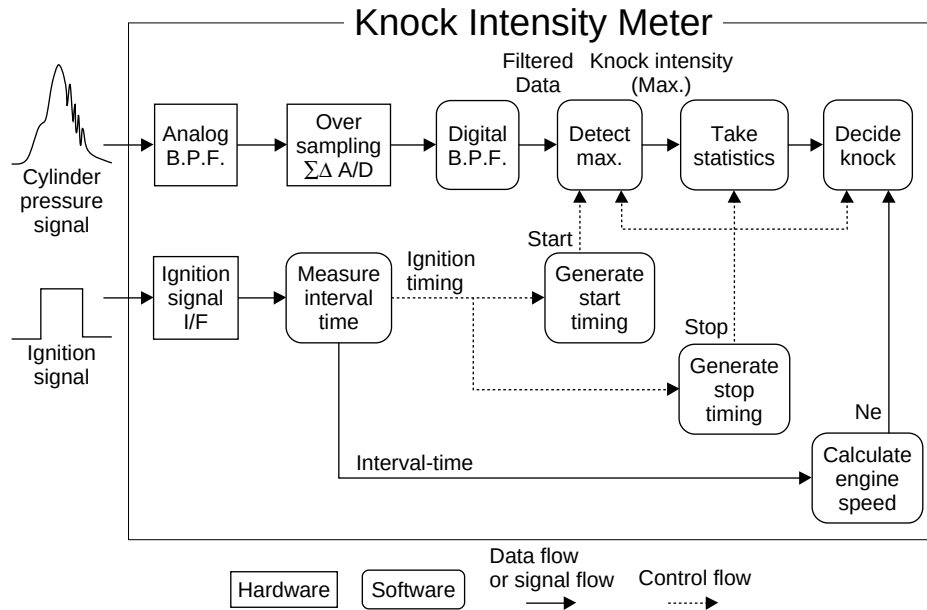


Fig.13 System diagram of knock intensity meter

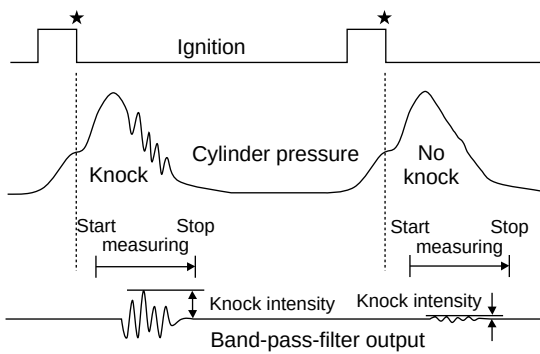


Fig.14 Timing chart of measuring signals



Fig.16 Appearance of knock intensity meter

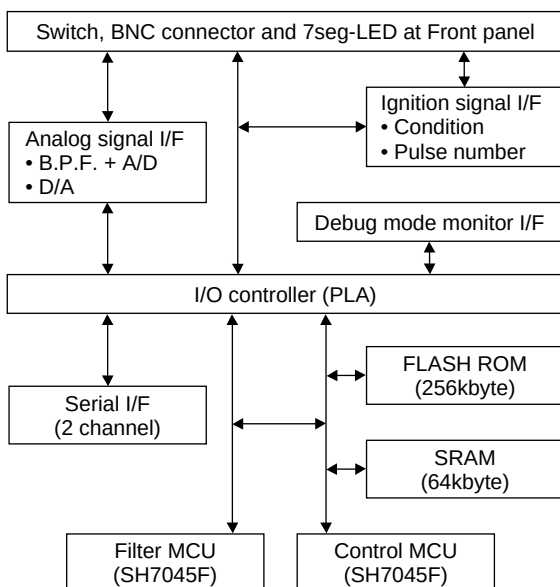


Fig.15 Constitution of hardware

5.2.1. Ignition Signal Interface

The signal level and pulse number can be selected to accommodate differences in the ignition system and distribution system. The following selections are available for the signal level:

- Battery voltage level (ignition edge: falling)
- Battery voltage level (ignition edge: rising)
- TTL level (ignition edge: falling)
- TTL level (ignition edge: rising)

The following selections are available for pulse number:

- Individual cylinder trigger (DLI or secondary side pickup of distributor power distribution); 1 pulse/720°
- Simultaneous firing ignition system trigger; 2 pulses/720°
- Simultaneous firing ignition system trigger (opposite

side cylinder); 2 pulses/720°

- Two-stroke engine trigger; 1 pulse/360°

In addition, the pulse number setting can be recognized by a processor for use in calculating the engine speed and other parameters.

5.2.2. Sensor Signal Interface

The analog filter consists of a high pass filter (1 kHz and above) for canceling the signals according to the combustion cycle, and a low pass filter (up to 100 kHz) to prevent aliasing distortion, these being connected in a cascade. Both filters are achieved with a low order CR filter and can be canceled by a jumper switch. In addition, a variable-gain (0.1-10) amplifier is installed between these two filters. The AD converter employs an oversampling SD modulation system that allows a relatively simple anti-aliasing filter to be used. This AD converter has a precision of 16 bits, an input range of -2 to +2 V, and the sampling rate can be switched between 25 kHz and 50 kHz. In addition, the sampling rate setting is recognized by a processor to perform coefficient switching of the digital filter.

5.2.3. Data Display Interface

The system is equipped with a 7-segment LED for stand-alone measurement. A single data group prepared in advance (such as the knock intensity or knock frequency) is selected, after which the physical quantities are displayed.

5.2.4. Knock Status Interface

A 12-bit D/A converter (output range: 0-5 V) is provided to give a TTL output and LED output corresponding to the results of the knock evaluation, as well as an analog output corresponding to the knock intensity, for connection to existing equipment and instruments. As a result, this can be used as an interlock, etc. during automatic operation.

5.2.5. Serial Communication Interface

A two-channel serial communication interface is provided for downloading the measurement results to a personal computer.

Since one of the serial communication interface channels allows connection to a network, the measurement results from multiple knock intensity meters can be incorporated with a single communications terminal.

5.2.6. Switch Signal Interface

The input from the sensor-type selection switch is identified by a processor as being either a charge amplifier output or a spark plug washer sensor output. This enables switching of the pass range of the digital filter and the knock evaluation algorithm.

The external switch input is recognized by the processor as a trigger in the case of rewriting or initializing (returning to the initial settings) the knock threshold value.

5.2.7. Processor

The system is equipped with two ordinary microprocessors (identical MCUs) containing built-in flash ROM. The functions are divided between the subprocessor that performs digital filtering and detects the maximum value of knock intensity, and the main processor that performs all the other tasks. All programs are assigned to the flash ROM contained within the processor, and both the main and subprocessor allow program rewriting by a flash writer. The main and subprocessor are connected in parallel and perform mutual monitoring. In addition, assigning knock threshold

values, filter coefficients and other constant data to external flash ROM makes it possible to accommodate rewriting and initialization of the knock threshold values by using an external switch for the trigger, as well as changing arbitrary constant data by connecting a personal computer for maintenance purposes.

5.3. Software

This section gives an overview of each process, including software processing that was not shown in Fig.13. In addition, it is necessary for this system to synchronize and process multiple external events, and it is equipped with a real-time OS complying with μ ITRON specifications for performing task management and other processing operations.

5.3.1. Pulse Processing

Pulse processing generates the timing (starting and ending) of the calculation and measurement of engine speed in synchronization with the ignition trigger. The timing for starting measurement detects the passage of a prescribed amount of time after the ignition trigger has been generated, while the timing for ending measurement detects the passage of a prescribed crank angle after the ignition trigger has been generated. Processing to generate the timing for ending the calculation and for measuring the engine speed is performed in consideration of the crank angle corresponding to one cycle of the ignition pulse according to the pulse set value of the ignition signal interface. However, in the case of actually generating the timing for starting and ending measurement, a delay in signal processing must be taken into consideration. Since the effect of this delay increases with increasing engine speed, the timing is generated by adding this delay time to both starting and ending points. Fig.17 shows a comparison between the ideal and actual measurement timing, which takes into consideration the delay, that are required as functions of the software.

5.3.2. Digital Signal Processing

Digital signal processing performs FIR filtering of a maximum of about 63 orders and updating of the maximum values of knock intensity at a sampling frequency of 25 kHz or 50 kHz. The filter coefficient is selected from four types

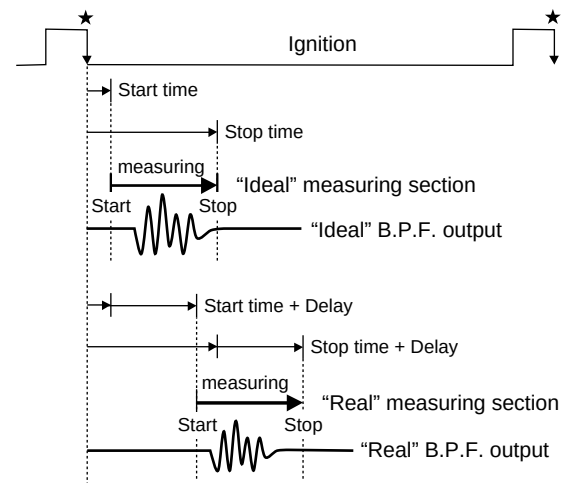


Fig.17 Measuring section

set in advance by combining the sampling frequency and sensor-type selection switches.

5.3.3. Statistical Processing and Knock Evaluation

Statistical processing (including the average value, standard deviation, peak value and knock frequency) is performed at a prescribed cycle interval for the above-mentioned maximum values. Moreover, a final evaluation of knocking is made according to the knock threshold value and the calculated results from statistical processing.

5.3.4. Processing of Each Output Means

The operation targets consist of the data display interface and knock status interface. The data display interface is used to select and display one of the following parameters corresponding to the display data selection switch:

- Calculation results of statistical processing
- Knock threshold value
- Engine speed

The knock status interface performs D/A output of the knock intensity and TTL output corresponding to the knock evaluation results. These interfaces are able to communicate with an automated measurement system to accommodate automatic operation.

5.3.5. Rewriting of the External Flash ROM

The following two methods are available for rewriting external flash ROM containing constant data:

- External switch
- Connection to a personal computer

In the case of rewriting the external flash ROM by an external switch, the knock threshold values are updated during normal operation or initialized (returned to the initial settings) during startup. For example, if the external switch is turned on during normal operation, the existing knock threshold values are replaced by newly calculated threshold values.

In the case of rewriting the external flash ROM by connecting to a personal computer, rewriting of all constant data used for maintenance is performed. For example, in the case of changing the knock resonance frequency as a result of changing the engine being measured or replacing the sensors, the newly set FIR filter coefficient can be updated using the personal computer.

compatible with automatic operation and automatic mapping.

Acknowledgments

The authors would like to take this opportunity to express their appreciation to Adtech System Science Co. Ltd. for their cooperation in the development of the measurement system.

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6. Conclusions

- 1) Knocking was quantified by passing the signal from a cylinder pressure sensor through a band pass filter and defining the maximum value as the knock intensity.
- 2) The quantified knocking data was correlated with test results obtained by hearing to confirm that the quantified data could be used for evaluating knocking.
- 3) A real-time measurement system was developed for quantifying and evaluating knocking that focuses only on the maximum values to achieve simple processing. In addition, this measurement system is compatible with various ignition signals and other sources as the timing signals, and it can be used with cylinder pressure sensors and spark plug washer sensors, giving it a high degree of flexibility.
- 4) The system has an interface for outputting knocking intensity and knocking evaluation flags, making it

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