

Construction of Knock Detection Logic by Pattern Recognition Using Short-time Fourier Transform

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ABSTRACT

The project discussed in this paper focused on the frequency attenuation characteristic of knock and mechanical noise in order to develop a more accurate method of distinguishing between the two phenomena. Short-time Fourier transform (STFT), which makes it possible to identify changes in frequency over time, was studied as a method of analyzing this characteristic. The duration of knocking is 80-90 deg in terms of crank angle. The frequencies of the multiple vibration modes that knock generates decline as time elapses, with attenuation greater in the high-frequency vibration modes, until finally only the 1,0th mode remains. Mechanical noise occurs over a wide frequency band, and its attenuation is rapid. Based on these results, the concept of time was introduced in order to help enable the attenuation of the frequencies to be identified, and a knock detection logic that judges knock on the basis of pattern recognition was developed. This logic is able to distinguish knock and mechanical noise with a high degree of accuracy even when the timing and frequency of the two phenomena match. As a result, it has been possible to increase robustness in relation to mechanical noise in comparison to conventional knock detection systems that judge knock based on the intensity of the frequency at which it occurs, helping to ensure stable functioning of the system even when mechanical noise occurs. This has made it possible to set the threshold value for judgment of knock lower than is the case in conventional systems, contributing to the reduction of knock noise.

1. Introduction

In order to increase the fuel efficiency of gasoline engines, high compression ratios are being employed in today's engines, resulting in an expansion of the range in which knock occurs, and at the same time a diverse range of devices are coming into use. Because many of these devices generate mechanical noise, a high-accuracy method of distinguishing mechanical noise is essential for knock detection systems using vibration sensors. It is challenging for conventional knock detection systems to distinguish between knock and mechanical noise when the frequency, intensity, and timing of the two phenomena match. A great deal of research focusing on the analysis of knock has been conducted in order to respond to this issue⁽¹⁾⁻⁽⁷⁾. Methods employed to assist in preventing an effect from mechanical noise in knock detection systems to date include the restriction of the range of detection⁽⁸⁾, the use, as a base, of a non-knock signal determined by deviation from a moving average obtained when no knock is occurring, the use of statistical methods⁽⁹⁾, and the use of trends in changes in sensor output⁽¹⁰⁾. However, because the mechanical noise generated by increasingly diverse devices, as typified by valve seating noise, displays a variety of frequencies,

intensities, and timings, it is challenging to detect knock using conventional methods.

The project discussed in this paper therefore attempted to enhance the method of distinguishing between knock and mechanical noise by newly introducing the concept of time and developing a knock detection logic employing pattern recognition. This paper provides an overview of this knock detection logic, considers methods employed in order to increase the accuracy of detection, and discusses the results of testing in an actual engine.

2. Issues of Knock Detection

Figure 1 shows a comparison of frequency and spectrum intensity characteristics when fast Fourier transform (FFT) processing is applied to non-resonance knock sensor output for knock and mechanical noise. When the frequencies and spectrum intensities match at the same timing, as shown by the circled areas in the graph, conventional knock detection logic employing band pass filters cannot distinguish between the knock and mechanical noise. It is therefore necessary to construct a knock detection logic that uses a method other than simple knock judgment when frequencies and spectrum intensities match.

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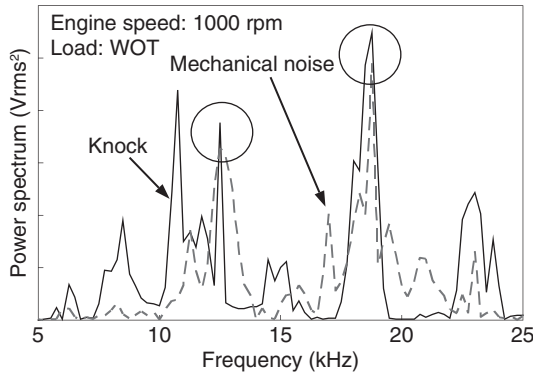


Fig. 1 Comparison of FFT processing results for knock and mechanical noise

3. Characteristics of Knock and Mechanical Noise

The difference in frequency attenuation characteristics between knock and mechanical noise was focused on in order to develop a more accurate method of distinguishing between the two phenomena. Short-time Fourier transform (STFT), which makes it possible to grasp changes in frequency over time, was studied as a potential method of analyzing these characteristics. STFT processing was applied to non-resonance knock sensor output when knock and mechanical noise were occurring, with results indicating that it was possible to clarify the difference between the two cases. The results of each analysis are discussed below.

3.1. Results of Knock Analysis

3.1.1. Duration of knock vibration

Figure 2 shows the non-resonance knock sensor output when knock occurs. As shown here, the amplitude of the knock waveform steadily declines with the passage of time. Figure 3 shows the results obtained when STFT processing is applied to the non-resonance knock sensor output when knock occurs. The X axis shows the crank angle, and the Y axis shows the frequency. The spectrum intensity is expressed by shade of the colors, with darker colors indicating stronger spectrum intensity.

Figure 3 indicates that knock vibration continues from the point of commencement of knock to approximately

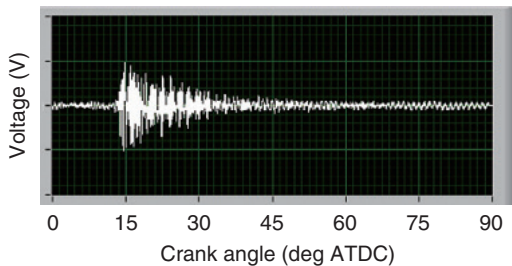


Fig. 2 Non-resonance knock sensor output when knock occurs

Table 1 Comparison of knock vibration duration for three different types of engine

Engine specifications	Displacement (cm ³)	1,339	1,799	2,354
	Bore x Stroke (mm)	73 x 80	81 x 87.3	87 x 99
Engine speed (rpm)	Intake manifold pressure (kPa (G))	Knock vibration duration (deg)		
1000	0 (WOT*)	95	82	90
	-20	90	85	92
2000	0 (WOT)	92	80	84
	-20	90	85	90
3000	0 (WOT)	89	90	91
	-20	89	83	89

* Wide-Open Throttle

ATDC 90 deg. This is thought to be because repeated air column vibration occurs due to the knock pressure wave. Table 1 compares the duration of knock vibration measured on a crank-angle basis using engines of differing displacements. These results indicate that knock vibration continued from the point of commencement of knock to approximately 80 to 90 deg, irrespective of displacement or load.

3.1.2. Phenomenon of frequency drop in vibration mode

Figure 4 shows the in-cylinder vibration modes generated by knock, and Eq. (1) shows Draper's equation⁽¹¹⁾. Figure 5 shows the results of STFT processing of the non-resonance knock sensor output when knock occurs, and frequencies calculated using Eq. (1) (shown as broken lines). Figure 5 indicates that the multiple vibration modes shown in Fig. 4 occur in the results of STFT processing of the non-resonance knock sensor output when knock occurs. The speed of sound when knock occurs in Fig. 5 was calculated from in-cylinder pressure using an equation of state as approximately 1000 m/s. Table 2 shows the results of obtaining the frequency of each vibration mode from these values using Eq. (1). The vibration mode frequencies shown in Table 2 display a high correlation with the frequencies obtained as a result of STFT processing of the sensor output when knock occurs shown in Fig. 5. In addition, the vibration mode frequencies in the STFT results display a tendency to decline as the expansion stroke progresses. From Eq. (1), this can be conjectured to represent a decline in

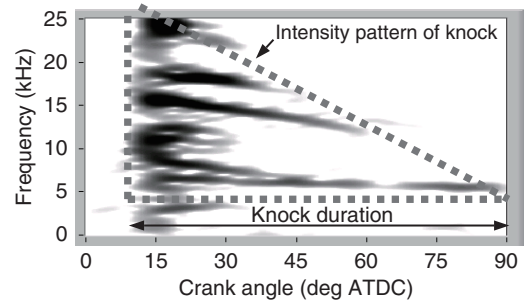


Fig. 3 STFT results when knock occurs

Table 2 Vibration mode frequencies immediately after knock occurs

Calculation condition: C=1000 m/sec D=87 mm					
	1,0 mode	2,0 mode	0,1 mode	3,0 mode	1,1 mode
Frequency (kHz)	6.8	11.3	14.2	15.6	19.8

the frequency of each vibration mode due to a decline in the speed of sound. The speed of sound was therefore determined from the output of a pressure sensor during the expansion stroke, and Eq. (1) was used to determine frequencies. The results of this procedure displayed the identical tendency as the results of STFT processing. Based on the results discussed above, it was judged that the frequencies of the multiple vibration modes generated by knock tend to decline because the speed of sound declines as the expansion stroke progresses.

$$f_{m,n} = \beta_{m,n} \frac{C}{\pi D} \quad (1)$$

Here,

$f_{m,n}$: Frequency

$\beta_{m,n}$: Vibration mode coefficient

C : Speed of sound

D : Bore diameter

3.1.3. Attenuation characteristics of vibration modes

The frequency of each vibration mode becomes attenuated as the expansion stroke proceeds, and at close to a crank angle of 90 deg only the 1,0th mode remains. This is thought to be because the pressure waves in the high-

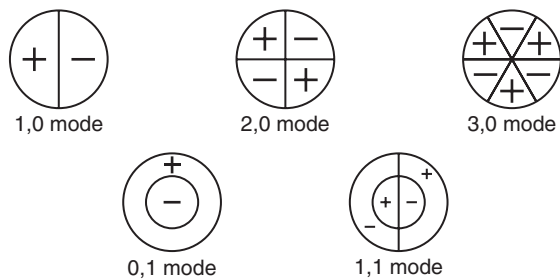


Fig. 4 In-cylinder vibration modes

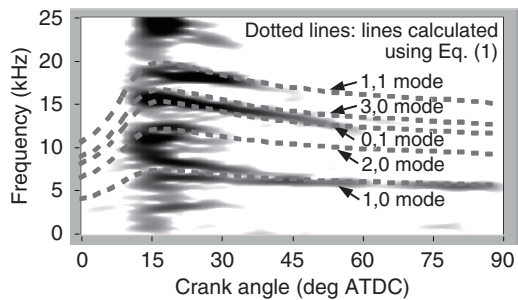


Fig. 5 Comparison of STFT results and curves calculated using Draper's equation

frequency vibration modes combine and become attenuated due to reflection and interference inside the cylinder.

3.2. Results of Analysis of Mechanical Noise

The major factor in most mechanical noise is impact. Typical mechanical noise includes the valve seating noise generated when intake and exhaust valves close. Figure 6 shows the non-resonance knock sensor output during valve seating. Figure 7 shows STFT processing results for valve seating noise, indicating that valve seating noise is generated over a wide frequency band. In addition, valve seating noise attenuates rapidly, and the duration of the vibration is approximately 1/5 that of knock, as discussed above. This is because the closing action of the valve, which is the vibration source for valve seating noise, undergoes forced convergence due to the valve train mechanism. This characteristic does not change even when the timing at which seating noise is generated changes due to the operation of continuously variable valve timing mechanisms.

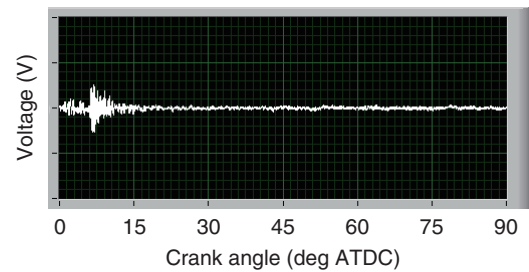


Fig. 6 Non-resonance knock sensor output when valve-seating noise occurs

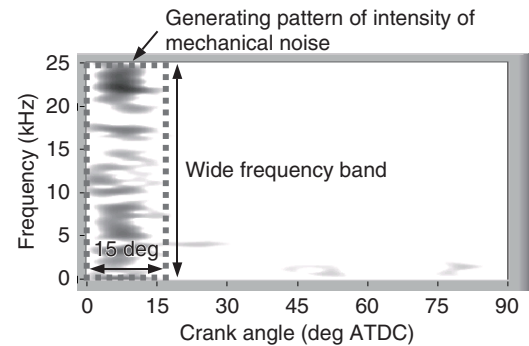


Fig. 7 STFT processing results for valve-seating noise

4. Methods of Distinguishing between Knock and Mechanical Noise

Based on the characteristics of knock and mechanical noise, a concept of time was newly introduced to make it possible to determine the attenuation of frequencies, and a new knock detection logic employing pattern recognition to identify knock was developed.

As shown in Fig. 3, because the results of STFT processing of sensor output when knock occurs demonstrate that the level of attenuation is high for high frequencies, and that in terms of crank angle the 1,0th mode continues over approximately 90 deg, the spectrum intensity displays a triangular distribution. In addition, as shown in Fig. 7, because the results of STFT processing of sensor output when mechanical noise occurs indicate that the noise occurs over a wide frequency band and its spectrum intensity attenuates rapidly, the spectrum intensity displays a rectangular distribution. These results are thought to indicate that the spectrum intensity distributions in the STFT results for knock and mechanical noise can be converted into patterns, and the two phenomena can be distinguished based on the differences between these patterns. Figure 8 shows pattern diagrams of the spectrum intensity distributions for knock and mechanical noise.

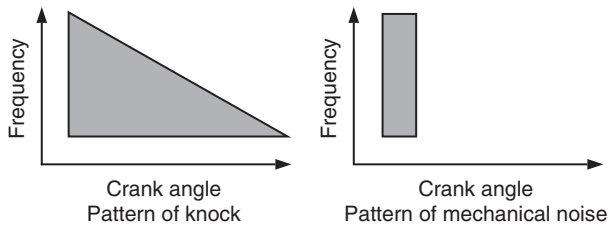


Fig. 8 Knock and mechanical noise intensity patterns

5. Knock Detection Logic

Figure 9 shows the processing flow for the STFT knock detection logic (“STFT logic” below).

- (1) STFT processing is applied in order to introduce the concept of time to the knock sensor output
 - (2) The results are stored in the frequency and crank angle map
 - (3) The noise component is removed in order to produce a map showing only knock
 - (4) Results are compared with the threshold values for judgment of knock, and binarization processing is applied
 - (5) Results are compared with the knock pattern, and knock is judged to occur where a correlation of 50% or more exists
 - (6) When knock is judged to occur, ignition timing is retarded in proportion to the conformance rate
 - (7) When knock is not judged to occur, the logic learns the conditions as a case of mechanical noise, and this judgment is employed in the next cycle
- These steps are discussed in greater detail below.

5.1. STFT Processing

STFT processing is applied to the non-resonance knock sensor output in the 12-78 deg ATDC interval in which knock occurs. Based on sampling theorem, from the

frequencies analyzed sampling is conducted at 50 kHz and above. In order to analyze frequency for each 1 kHz, the time constant is set at 1 msec, and frequency components are calculated for every 6 deg. The results of this STFT processing are stored on an STFT map of the type shown in Fig. 10, composed of 66 squares, with frequency from 5-23 kHz divided into six groups and crank angle from 12-78 deg divided into 11 groups, one for each 6 deg. The map on which the knock spectrum intensity distribution is arranged into patterns is termed the master map; this is shown as the shaded section in Fig. 10. The figures on the master map show coefficients for raising the threshold value for knock judgment, which will be discussed below.

5.2. Isolation of Vibration Modes

In order to identify the vibration mode frequencies, which display a decline with the passage of time, the frequencies in the STFT processing results calculated for each 1 kHz are divided into groups as shown in the STFT map in Fig. 10, and the maximum spectrum intensity for each group is selected. By means of this processing,

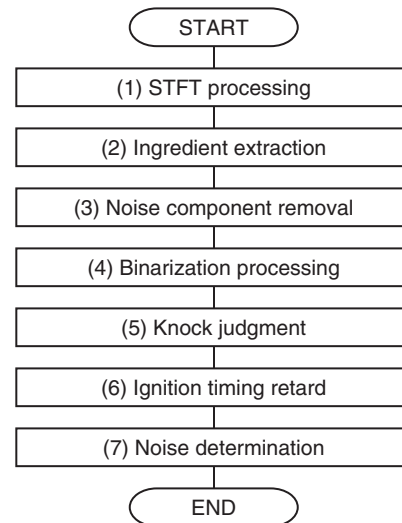


Fig. 9 Knock detection logic processing flow

		Crank angle (deg ATDC)										
		12	18	24	30	36	42	48	54	60	66	72
Frequency band (kHz)	20 - 23	1	1									
	17 - 19	1	1	1								
	14 - 16	1	1	1	1							
	11 - 13	1	1	1	1	1						
	8 - 10	1.25	1.5	2	2	1.5	1.25					
	5 - 7	1.25	1.5	2	2	1.5	1.25	1	1	1	1	1

Master map
Numbers in the master map show coefficient of boosting knock judgment threshold value

Fig. 10 STFT map, master map, coefficient of boosting knock judgment threshold value

it is possible to grasp the phenomenon of the decline in frequency of each of the vibration modes generated by knock. The calculated results are termed the maximum intensities map.

5.3. Removal of Noise Components

When knock is not judged to occur, a noise learning map based on the system's previous learning of continuously generated mechanical noise is employed. The difference between this map and the aforementioned maximum intensities map is calculated for each grid point. By means of this processing, a map that expresses only knock is produced. This map is termed an intensity distribution map.

5.4. Binarization Processing

The values on the intensity distribution map are compared with the threshold value for knocking judgment. When the value is greater than the threshold value it is converted to "1," and when it is lower it is converted to "0." This processing converts the intensity distribution map into a map that shows the intensity generation pattern. This is termed the pattern map.

Figure 11 shows the threshold value for knock judgment. This value is set to help enable detection of trace knock. In addition, taking the frequency band on the master map in which the intensity becomes stronger when knock is produced and the knock attenuation characteristic into consideration, a coefficient for raising the threshold value for knock judgment (as shown in Fig. 10) is applied in order to partly raise the threshold value. This method increases the robustness of the system, helping it to maintain stable functioning even when mechanical noise is being generated. Non-continuous mechanical noise, such as piston slap, is also generated when water temperature is low, and the threshold value for knock judgment is also raised in order to increase robustness in relation to mechanical noise at low water temperatures.

5.5. Judgment of Knocking

The intensity generation pattern on the pattern map calculated using binarization processing and a previously determined knock intensity generation pattern are compared, and the level of correlation between the two is calculated. The calculated value is termed the conformance

rate. Knock is judged to occur when the conformance rate is 50% and above.

The timing of knock generation changes depending on the ignition timing and the speed of combustion. In Fig. 10, the master map commenced from 12 deg, but the start position of the master map is adjusted depending on ignition timing and whether or not exhaust gas recirculation (EGR) is performed. Figure 12 shows the relationship between ignition timing, EGR, and the start position of the master map.

5.6. Retardation of Ignition Timing

Following judgment of knocking, ignition timing is retarded the necessary minimum amount in relation to the conformance rate, which indicates the intensity of knock. Figure 13 shows the relation between the conformance rate and the degree of retardation of ignition timing. In the previous system, ignition timing was retarded by a fixed degree when knock was judged to occur, but the newly developed system determines the optimum degree of retardation of ignition timing in response to the conformance rate. This helps to prevent excessive or insufficient retardation of ignition timing, and makes it possible to reduce knock without causing fuel efficiency to decline.

5.7. Noise Learning

Valve seating noise is a representative example of mechanical noise. Valve seating noise occurs frequently, and is stable because the energy involved is determined by

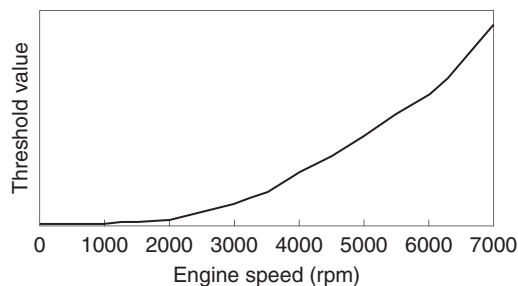


Fig. 11 Knock judgment threshold value

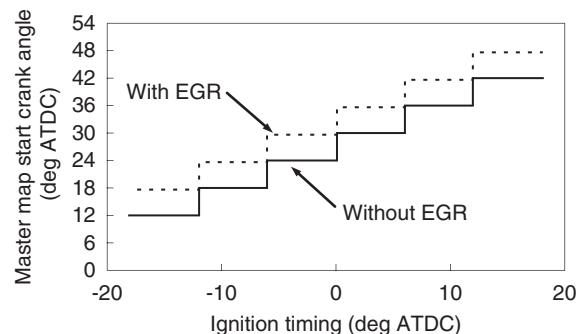


Fig. 12 Start timing of master map

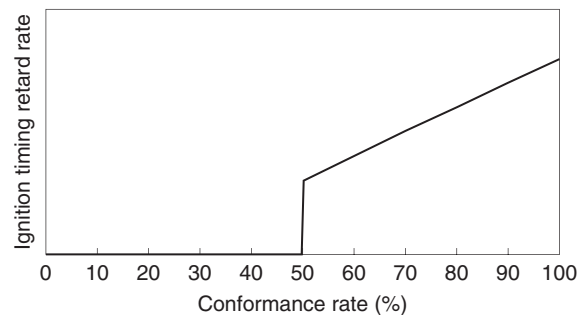


Fig. 13 Knock retard for conformance rate

the mass of the valve body and the spring coefficient of the valve spring. When knock is not judged to occur, the logic learns the conditions as a case of mechanical noise, and this is employed as a noise learning map in the next cycle. The noise learning map corrects for changes in engine speed, and is calculated using weighted averages with past values.

6. Verification of STFT Logic

6.1. Test Engine Specifications

A Honda 2.4-liter DOHC-VTEC-L4 engine equipped with a Variable valve Timing and lift Electronic Control (VTEC) mechanism and a VTC system for the intake valve camshaft was employed as the test engine. Table 3 shows the engine specifications.

Table 3 Engine specifications

Cylinder configuration	In-line 4-cylinder
Bore x Stroke (mm)	87 x 99
Displacement (cm ³)	2354
Compression ratio	10.5
Valve train	DOHC (inlet: valve timing control)
Number of valves	4 valves / cylinder
Fuel injection system	Port injection

Table 4 Operating conditions

Engine speed (rpm)	Intake manifold pressure (kPa (G))
1000	-20
1000	0 (WOT)
3000	-20
3000	0 (WOT)
6000	-20
6000	0 (WOT)

6.2. Check of STFT Logic when Knock is Detected

Table 4 shows the engine speed and load conditions used in the tests. The operation of the STFT logic was checked by analyzing the STFT logic results for a cycle in which knock occurred under each test condition.

Figure 14 shows STFT processing results when knock occurred. The X axis of the graph shows the crank angle, and the Y axis shows frequency. The spectrum intensity is expressed by the shade of the colors, with lighter colors indicating stronger spectrum intensity.

The white areas in Fig. 14 show the spectrum intensity produced by knock. The same knock vibration modes, and the frequency drop in those modes, as shown in Fig. 5 can be observed in Fig. 14. In addition, this figure shows that attenuation as the expansion stroke progresses is greater in the high-frequency vibration modes. Based on these results, the STFT logic was judged as being able to accurately identify the characteristics of knock. Figure 15 shows the intensity distribution map calculated by the STFT logic from the STFT processing results in Fig. 14. This figure indicates that the calculated intensity distribution map is able to isolate the knock vibration modes in which frequency declines over time from the STFT calculation results shown in Fig. 14. Figure 16 shows pattern map calculation results when knock occurs. Here, the intensity distribution map when knock occurs is subjected to binarization processing and converted into a pattern displaying the knock features shown in Fig. 8. Calculation of the conformance rate for Fig. 16 produced a result of 93%; the conformance rate exceeds 50%, and knocking is judged to occur. Based on these results, the STFT logic was judged as correctly reproducing the knock pattern.

6.3. Verification of Knock Detection Accuracy

An in-cylinder pressure sensor was fitted in an engine, and the detection accuracy of the STFT logic was verified by comparison with the pressure sensor output. In order to judge knock in the pressure sensor output, the output was processed using a band pass filter (5 kHz to 10 kHz) and calculated values were compared with a threshold value for

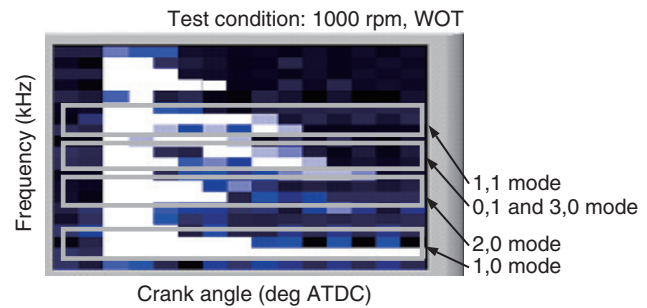


Fig. 14 STFT calculation results

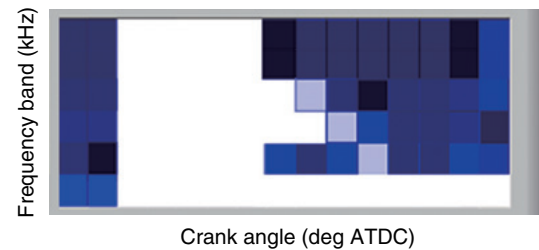


Fig. 15 Knock energy calculation results

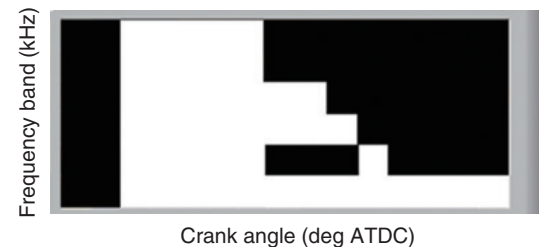


Fig. 16 Pattern map calculation results when knock occurs

Table 5 Comparison of knock detection logic detection count for varying conditions

Engine speed (rpm)	Intake manifold pressure (kPa (G))	Number of times of knock detection in 50 cycles	
		STFT logic	In-cylinder pressure logic
1000	-20	6	6
1000	WOT	8	8
3000	-20	8	8
3000	WOT	7	7
6000	-20	11	11
6000	WOT	8	8

judgment of knock. Figure 17 shows the configuration of the measurement system.

Figure 18 shows time charts of the knock output obtained by the in-cylinder pressure sensors under conditions of almost continuous knock and the conformance rate calculated by the STFT logic. These results confirm that both knock detection logics detected knock in the same cycle. Table 5 shows the knock detection count for each logic under different engine speed and load conditions. Even under different engine speed and load conditions, both knock detection logics displayed equivalent detection

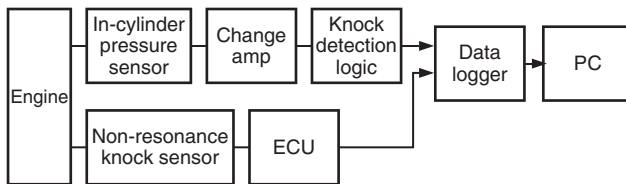


Fig. 17 Measuring system configuration

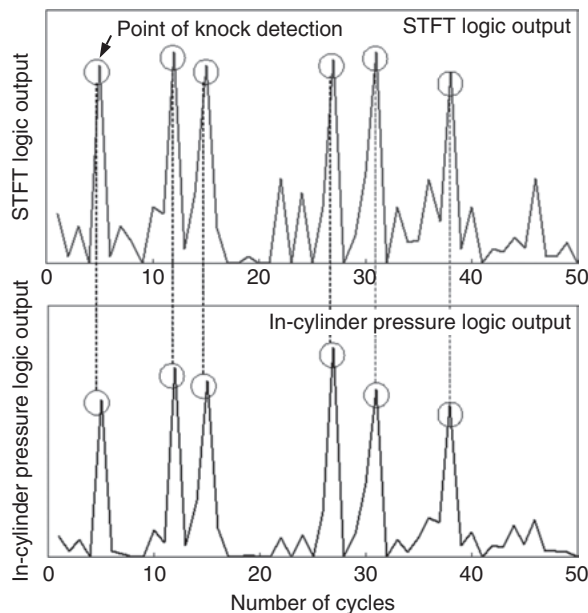


Fig. 18 Comparison of in-cylinder pressure sensor knock output and conformance rate

performance. The STFT logic was therefore judged as being able to accurately detect knock.

6.4. Verification of Robustness in relation to Mechanical Noise

Valve seating noise was generated within the knock detection gate, and knock detection was performed to verify the robustness (stable system functioning) of the STFT logic in relation to mechanical noise.

The upper graph in Fig. 19 shows knock output for the band pass filter logic and the threshold value for judgment of knock. The lower graph in Fig. 19 shows the conformance rate for the STFT logic and the conformance rate of 50% at which knock is judged to occur.

In the case of the band pass filter logic, when valve seating noise occurs within the knock detection gate, knock output increases compared to the output when valve seating noise is not generated, and exceeds the threshold value for knock detection at some points. This indicates that the band pass filter logic misjudges mechanical noise as knock. By contrast, the conformance rate calculated by the STFT logic does not increase significantly when valve seating noise is generated within the knock detection gate, indicating that mechanical noise is not misjudged as knock.

Figure 20 shows the pattern map calculated by the STFT logic when valve seating noise occurs. This figure

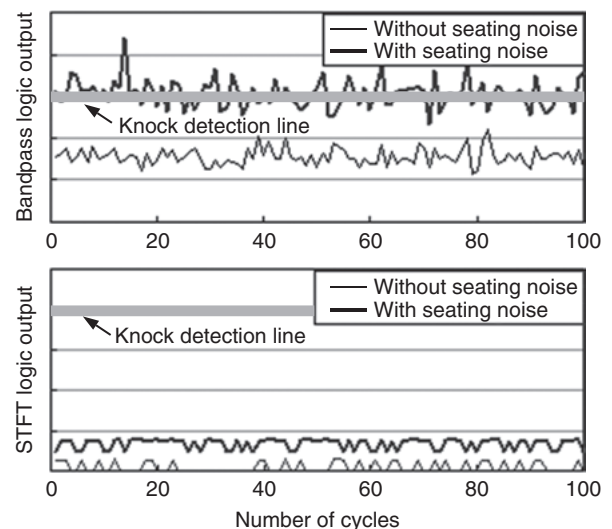


Fig. 19 Knock judgment output results for each logic when seating noise occurs

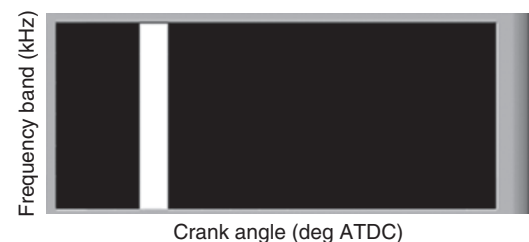


Fig. 20 Pattern map when valve-seating noise occurs

demonstrates that the valve seating noise pattern calculated by the STFT logic displays a wide frequency band. This valve seating noise pattern clearly differs from the knock pattern shown in Fig. 16. Therefore, the conformance rate calculated by the STFT logic does not increase, and does not lead to misjudgment of knocking. Based on these results, pattern processing by the STFT logic is judged as providing the system with greater robustness in relation to mechanical noise than conventional knock detection systems that judge knock based on the intensity of the frequency at which it occurs.

The results discussed above demonstrated that the newly developed system is able to distinguish knock and mechanical noise with a high degree of accuracy even when the timing and the frequency of the phenomena match. In addition, increasing the robustness of the logic in relation to mechanical noise has made it possible to set the threshold value for judgment of knock lower than is the case in conventional systems, and this contributes to the reduction of knock noise.

7. Conclusion

A knock detection logic able to distinguish knock and mechanical noise with a high degree of accuracy was developed. The following results were obtained from this development.

- (1) Using STFT, the concept of time was introduced in order to help enable the attenuation of frequencies to be identified, and a knock detection logic that judges knock on the basis of pattern recognition was developed. This logic is able to distinguish between knock and mechanical noise with a high degree of accuracy even when the timing and frequency of the two phenomena match, and has made it possible to increase robustness in relation to mechanical noise against conventional knock detection systems that judge knock based on the intensity of the frequency at which it occurs.
- (2) Increasing the robustness of the logic in relation to mechanical noise has made it possible to set the threshold value for judgment of knock lower than is the case in conventional systems, and this contributes to the reduction of knock noise.

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