Error-free Detection of Knocking Combustion Using Wavelet Transform for SI Engine

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Abstract

This study examined the application of wavelet transforms to signal processing to improve the reliability of knock detection. It was expected that this method would make it possible not only to keep track of continuous knock vibrations, but also to detect vibrations occurring and disappearing instantaneously. For this the scale-spectrum comparison method was proposed as the method of knock detection. This method focuses on the components of resonant vibration that are specific to the engine, and compares their scale power spectra with each other in real time. A 4-cycle gasoline engine was used for the experiment. Cylinder pressure sensors and a vibration sensor were attached, and a comparative examination of the knock detection performance of the two signal processing methods, the conventional Fourier transform method and the proposed scale-spectrum comparison method, was carried out. Data over the whole operating range of the engine was obtained, and the data showed that it was possible to reduce both errors and mistakes as compared with the conventional method.

Keywords : Knocking Detection, Wavelet Transform, Scale-spectrum Comparison Method, SI Engine

Introduction

In a spark-ignition engine, knock control is widely used to produce optimum combustion, whatever the driving conditions or changes in fuel properties. Normally, a vibration sensor is attached to the cylinder block and the timing of the ignition is controlled by detecting components of resonant vibrations in the vibration sensor signal, because these vibration components indicate the occurrence of knocking. The reliability of this method of knock detection decreases as the engine speed or load increases, because of the increase in background noise. It is desirable to find a proposal for a detection method which minimizes errors, which are erroneous detections of knocking, and misses, which are failures to detect knocking (this is called error-free detection below).

Because the current knock detection method compares the combustion characteristics of the past several times of combustion and the combustion characteristics of the current time of combustion, a delay in response occurs. Because this detection method uses a Fourier transform, there is a

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limit to the minimum numbers of waves necessary for detection, also reducing the sensitivity. These may cause detection errors, and control performance is not necessarily satisfactory for driving with frequent acceleration and deceleration.

To eliminate the delay in knock detection, this study examines a method to detect a knock for each combustion in an independent manner without using the past trend. The sensor used was a conventional type, or a vibration sensor. It was decided to apply a wavelet transform, rather than a conventional Fourier transform, to signal processing, because the former is thought to be advantageous in grasping the characteristics of local state changes. In the course of examining detection methods in an experimental way, a basic method for signal processing was first established using an in-cylinder pressure sensor, and then its performance was compared to the conventional method using a practical vibration sensor. As a result, a scale spectrum comparison method using a wavelet transform was proposed, and a reduction of detection errors by this was confirmed by an engine experiment.

Knock control & experimental system

Knock control is a method that intentionally generates minimal knocking and keeps its frequency properly. Knocking is detected as resonant vibrations of in-cylinder pressure, and vibrations that travel to a cylinder block are normally measured by an acceleration sensor. The occurrence of knocking is determined by using its vibrational energy. In the conventional method of knock detection, the power spectrum of a resonant frequency specific to an engine is extracted through a bandpass filter or a digital filter (FFT). Ignition timing is gradually advanced. Then, when the size of the frequency power spectrum exceeds a prescribed level, it is judged as the occurrence of knocking, and ignition timing is retarded. In knock control, this process is repeated, and ignition timing is advanced by the average. Therefore, the maximum torque is consistently obtained without the influence of fuel properties, operating conditions, individual differences of engines, differences among cylinders, etc. Resonant vibrations occur to some extent even in ordinary combustion caused by fire propagation, and have an influence on knock detection as noises. For this reason, a method that learns expected values from combustion data several times in the past and compares them is adopted. This learning process causes detection delays, and worsens the performance of control under acceleration. This study aims at eliminating the learning process of noise levels and detecting knocking in one combustion stroke.

Knocking is a phenomenon that appears and vanishes in a short period of time in a combustion stroke. Therefore, for the improvement of the sensitivity of detection, it is considered that a wavelet transform, which can grasp the characteristics of local changes of state in comparison with a conventional Fourier transform, would be effective. In this study, the effect of the application of a wavelet transform is experimentally examined. Figure 1 shows the experimental system. A PC for analysis was installed in parallel with an engine control unit, and a spark plug that includes in-cylinder pressure sensors and vibration sensors were attached

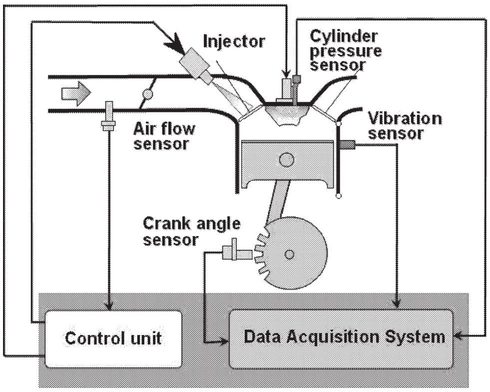


Fig. 1 Experimental system

to an engine. In-cylinder pressure signals, vibration signals and crank angle signals were simultaneously measured through a 14-bit A/D converter. Because the frequencies of resonant vibrations that knock control covered were within 20 kHz, it was decided that the sampling period would be 10 μs, and wavelet transforms were conducted for imported data using the same PC.

Scale-spectrum comparison method

Six types that are shown in Figure 2 can be considered as resonant vibration modes of knocking. The circular form indicates a top view of a cylinder, and the quadrangle indicates a side view of a cylinder. A1 and A2, which are primary circumferential modes, pair up with B1 and B2, which are secondary circumferential modes. In addition, C1 is a primary radial mode, and D1 is a primary axial mode. The dashed line indicates the nodes of the oscillation of an air column, and "+" and "−" respectively indicate the higher part and the lower part of the pressure in a cylinder.

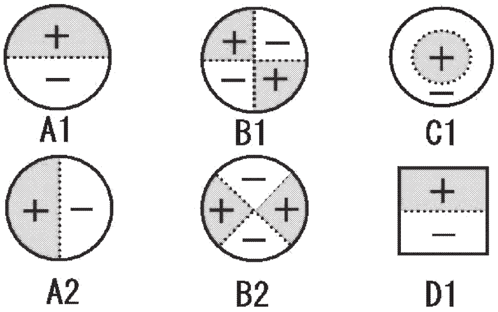


Fig. 2 Resonant-vibration modes of knocking

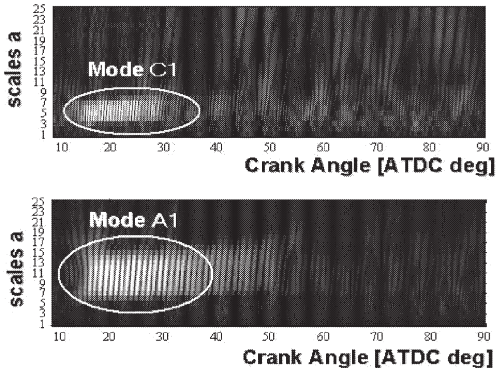


Fig. 3 Different modes in the same crank angle

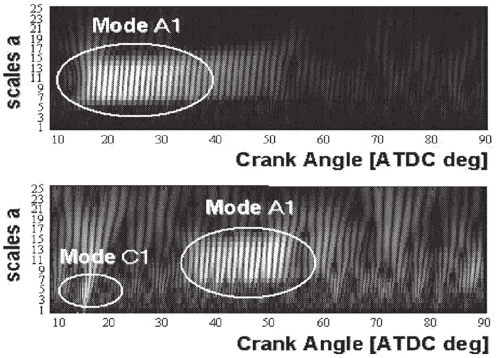


Fig. 4 Same mode in different crank angles and different mode in the same combustion

Figure 3 and Figure 4 show the measured data that were obtained from experiments of an engine and the example of the occurrence of knocking from the results of wavelet transforms. In the upper part of Figure 3, the characteristics of knocking are grasped at 15 to 30 degrees of crank angles ATDC. Scales are 4 to 7, and there is a power component like a white belt. As a result of calibration, it was found that the power component corresponded to the resonant vibration mode C1. Also in the lower part of Figure 3, knocking is grasped at 15 to 30 degrees of ATDC. However, the scales are 6 to 14, and the resonant vibration mode is A1. In the lower part of Figure 3, the resonant vibration mode C1 is grasped at 15 degrees of the crank angle ATDC, and the resonant vibration mode A1 is grasped at 35 to 53 degrees of the crank angles ATDC. From these results, the following findings are obtained:

(1) Even at the same crank angle, different resonant vibration modes occur. (in the upper part of Figure 3 and the lower part of Figure 3)

(2) Even at different crank angles, the same resonant vibration mode occurs. (in the upper part of Figure 4 and the lower right part of Figure 4)

(3) Even in the same combustion process, different resonant vibration modes occur depending on crank angles. (in the lower left part of Figure 4 and the lower right part of Figure 4)

(4) Plural resonant vibration modes do not simultaneously occur dominantly. (all)

From experiments with an engine, it was found that the identification of various resonant vibration modes was important for knock detection. In particular, from many experimental results obtained by the author and other persons, it is judged that the fact that plural resonant vibration modes do not simultaneously occur locally is a general characteristic. In addition, the difference of resonant vibration modes can be discriminated by scales. By using this finding, a method that can detect knocking in one combustion stroke without the learning process is planned.

Figure 5 shows a new knock detection method that is a scale-spectrum comparison method. (1) Scale power spectra are determined for resonant vibration modes. Here, resonant vibration modes of A1, B1, and C1 are shown. Corresponding scales are 12, 8, and 6. (2) At a certain crank angle, scale power spectra that correspond to resonant vibration modes A1, B1, and C1 are compared mutually. The details are as follows. The engine is started at every stroke of combustion. First, depending on crank angles, in-cylinder pressure signals are sampled at a high speed from 0 to 60 degrees of crank angles ATDC, which are regarded as the domain where knocking occurs. Then, filtering is conducted in the frequency domain from 5 to 20 kHz. Next, depending on crank angles, scale power spectra P_A, P_B, and P_C are determined at scales a of 12, 8, and 6 that correspond to resonant vibration modes A1, B1, and C1. Then, the crank angle zone A that corresponds to large P_A is determined.

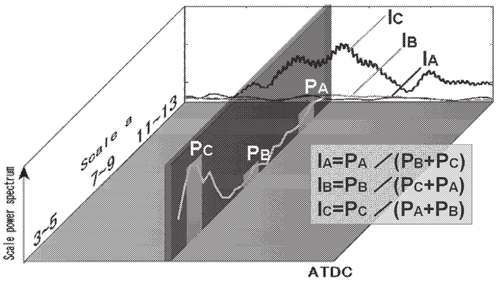


Fig. 5 Scale-spectrum comparison method (proposed)

In the crank angle zone A, P_{AEA}, P_{BEA}, and P_{CEA}, that is, the average values of P_A, P_B, and P_C, are determined. The ratio of P_{AEA} and the sum of P_{BEA} and P_{CEA} is determined, and the result is defined as the index P_{NA} that indicates knock intensity. In the same manner, P_{NB} and P_{NC} are also determined. If one of the two knock indexes P_{NA}, P_{NB}, and P_{NC} exceeded the threshold value P_N, it is judged that knocking occurred. If all the knock indexes P_{NA}, P_{NB}, and P_{NC} do not exceed the threshold value P_N, it is judged that knocking did not occur.

Knock detection in one combustion

Figure 6 to Figure 8 show the examples of experimental results where knock detection was conducted by using the proposed scale-spectrum comparison method. The operating condition is 2,000 rpm at a constant state. A threshold value for the judgment of knocking is set to prevent wrong judgment arising from the variation of combustion, and $P_N=1.5$ was set here. In Figure 6, the knock indexes P_{NA}, P_{NB}, and P_{NC} were sequentially compared with, P_N and $P_{NC}>P_N$ was judged as the occurrence of knocking. Similarly in Figure 7, $P_{NA}>P_N$ was judged as the occurrence of knocking. Figure 8 shows an example where it was judged that no knocking had occurred, because the knock indexes P_{NA}, P_{NB}, and P_{NC} did not exceed the threshold value P_N. From these results, it was proved that knocking could be detected in one combustion stroke.

Figure 9 shows an example of experimental results under acceleration. Figure 9 (a) is a waveform of in-cylinder pressure. Acceleration was started from 850 rpm at the 1st hill, and the speed at the 3rd hill is 3,000 rpm. Figure 9(b) and (c) show the results where the scale-spectrum comparison method was applied to the 1st hill and the 3rd hill. In Figure 9(b), knocking was not detected. However, in Figure 10 (c), knocking was detected in the range of crank angles from 9 to 13 degrees. From these results, it was proved that knocking could be detected also under acceleration by using the same threshold value as at a constant state.

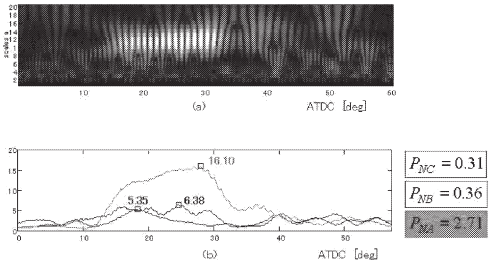


Fig. 7 Example detecting knock with mode A

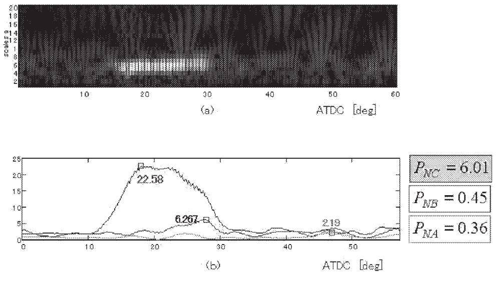


Fig. 6 Example detecting knock with mode C

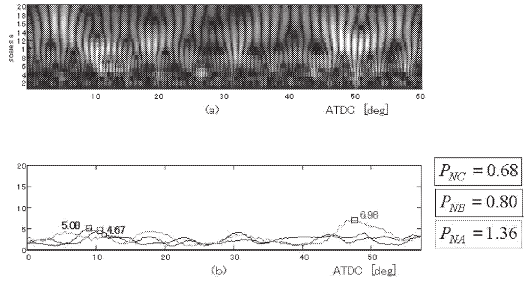
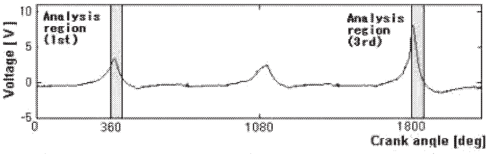
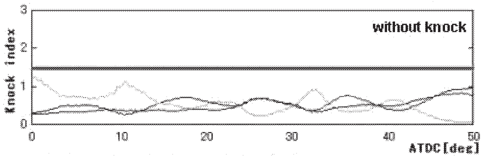


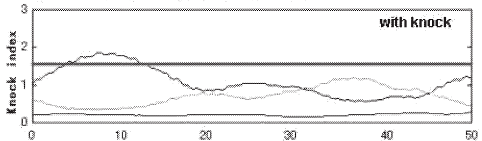
Fig. 8 Example not detecting knock



(a) Cylinder pressure at the time of acceleration



(b) Knock detection at the 1st hill



(c) Knock detection at the 3rd hill

Fig. 9 Knock detection at the time of acceleration

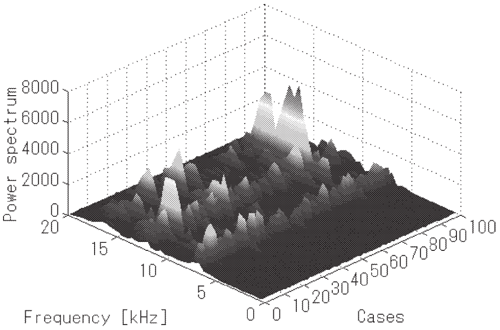


Fig. 10 Trend of frequency-spectrum of in-cylinder pressure signals

Reducing detection errors

The current engine uses not an in-cyclinder pressure sensor, but a vibration sensor. Therefore, the S/N ratio of the signal decreases and detection errors occur. It was examined whether the scale spectrum comparison method has the effect of reducing such detection errors.

For judgment of the occurrence of knocking, the results obtained using the in-cylinder pressure sensor were used as a reference. The signal of the vibration sensor was transformed into a Fourier transform and compared with this reference. The results of this comparison and the results obtained using the scale spectrum comparison value (knock index) are shown in Table 1. The judgment results shown here concern the data obtained for 100 consecutive times of combustion at 1,200 and 5,000 rpm, respectively.

Detection errors were defined here as follows:

True: Occurrence of knocking judged according to the in-cylinder pressure sensor signal and occurrence of knocking judged according to the vibration sensor signal

Miss: Occurrence of knocking judged based on the in-cylinder pressure sensor signal, but absence of knocking judged according to the vibration sensor signal

Error: Absence of knocking judged according to the in-cylinder pressure sensor signal, but occurrence of knocking judged according to the vibration sensor signal

Table 1 shows examples of knock detection at 1,200 rpm, using the in-cylinder pressure signal.

Where

fp: Fourier spectrum method using the in-cylinder pressure sensor signal (used as a reference of knock judgment)

fv: Fourier spectrum method using the vibration sensor signal (current method)

wv: Scale spectrum comparison method using the vibration sensor signal (proposed method), “1”: occurrence of knocking, “0”: absence of knocking.

Knocking was detected 3 times per 100 combustions at 1,200 rpm. For these

Table 1 Comparison of the knock detection in combustion of 100 continuations at 1,200 rpm

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25			
fp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0			
fv	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0			
wv	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0			
No.	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50			
fp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0			
fv	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0			
wv	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0			
No.	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75			
fp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0			
fv	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0			
wv	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0			
No.	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	True	Miss	Error
fp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	-	-
fv	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	2
wv	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0

knocks, the results (fv) of the Fourier transform using the vibration sensor signal caused no Miss judgments, but 2 Errors. By the method of applying the scale spectrum comparison method, the results (wv) were improved to no Miss judgments and no Errors at 1200 rpm.

Conclusions

Knock control is applied to combustion optimization of gasoline engines, and this study strived for performance improvement of knock control. In conventional knock detection, there is a delay due to learning the past combustions, and this lowers the control performance during accelerating driving.

Based on engine experiments, this study

(1) found that multiple resonant vibration modes do not occur simultaneously.

(2) proposed a scale spectrum comparison method using a wavelet transform.

(3) found that the scale spectrum comparison method can detect a knock in one combustion, and that it can also be applied during accelerating driving.

(4) confirmed that detection errors can be reduced by applying the scale spectrum comparison method to a practical vibration sensor.

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