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Research Report

Noise-canceling Spike Combustion: A New Concept to Reduce Combustion Noise by Interference of Two Pressure Rise Peaks

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ABSTRACT A combustion system that reduces combustion noise using premixed charge compression ignition (PCCI) with split injection of fuel was studied. In addition to the noise reduction by lowering the peak of the pressure rise rate, combustion noise spectra analysis showed that noise-canceling occurs between the two peaks in the pressure rise rate at the optimal second injection timing, which reduces the overall combustion noise by reducing the maximum frequency component of the noise spectrum. The period of this frequency is twice as long as the interval between the two peaks in the pressure rise rate. We refer to this noise reduction technique as noise-canceling spike combustion because it relies on interference between a spike in the pressure rise with the preceding peak in the pressure rise. The maximum load range of conventional PCCI combustion is limited by the combustion noise because the maximum pressure rise rate increases with the amount of fuel being injected. Noise-canceling spike combustion has the potential to extend the operating range of PCCI combustion. In addition, noise-canceling spike combustion can occur between two heat releases of the pilot and main injection fuels in diesel combustion with multi-injection.

KEYWORDS Compression Ignition Engine, Diesel Engine, PCCI, Combustion Noise, Noise-canceling

1. Introduction

Diesel engines have high thermal efficiency, although exhaust emissions such as NO_x and soot remain a serious issue. Combustion noise is also an important issue for diesel engines. The typical heat release pattern for diesel combustion is shown by the black line in **Fig. 1** (a). The fuel injected during the ignition delay period leads to premixed combustion, and then diffusive combustion occurs. The rapid heat release of the premixed combustion induces loud combustion noise. Pilot injection, which shortens the ignition delay period of the main injection fuel, has been commonly used since the emergence of the common rail type injection systems to reduce the ratio of premixed combustion. However, the combustion noise still remains a serious issue for diesel combustion.

New combustion systems, homogeneous charge compression ignition (HCCI)(1-3) and premixed charge combustion ignition (PCCI)(4-6) have been examined with the aim to achieve clean exhaust gas by reducing NO_x and soot. However, combustion with these premixed type combustion systems becomes very steep, which results in a very high heat release rate and a very short duration of the heat release; therefore, the combustion noise becomes very high (Fig. 1 (b)). High combustion noise is one of the obstacles to the extension of the maximum load range of HCCI/PCCI combustion. Reactivity controlled compression ignition (RCCI),(7-9) which lowers the heat release rate by blending two fuels with different reactivity, has been studied by Inagaki et al. and by Reitz's group; however, RCCI is not yet in practical use.

We have demonstrated that PCCI combustion with split injection can achieve low fuel consumption, low exhaust emissions, and low combustion noise.(10) In this combustion system, the two-stage combustion by split injection reduces the peak height of the heat

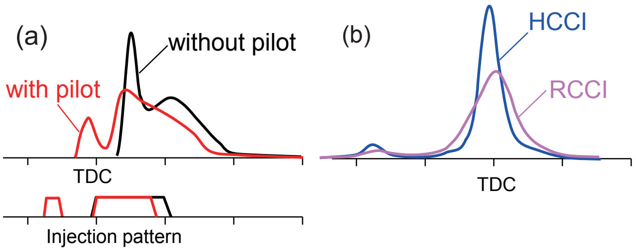

Fig. 1 Histories of heat release rates; (a) Diesel combustion, (b) HCCI and RCCI combustion.

release rate, and thereby reduces the combustion noise (**Fig. 2**). In addition, the combustion noise can be reduced further by the interference of sound pressure waves, which can be controlled according to the time interval between two peaks of heat release rate.(11) The authors refer to this noise reduction technique that exploits the interference of sound pressure waves as noise-canceling spike combustion.

In this paper, the authors review the studies on combustion noise in diesel/compression ignition combustions, and introduce details of the noise-canceling spike combustion technique.

2. Review of Combustion Noise Analysis

The mechanism of noise emitted from diesel engines has been studied for a long time.(12–14) The noise emitted from diesel engines is classified into two types according to the source; one is combustion noise and the other is mechanical noise. Combustion noise is generated by the in-cylinder pressure pulse that impacts on the surface of the combustion chamber and acts like a bell hammer.(13) Mechanical noise is generated by impacts of mechanical parts such as gears between the crankshaft and cam-shafts. Some researchers regard the piston slap noise as a typical example of mechanical noise, while others have classified it as a third type of noise. The vibrations generated by these sources transmit through engine parts such as the cylinder head, cylinder block, and crank case, and then reach the external surfaces of the engine. The engine noise is finally emitted from the surface of the engine. In this work, only the combustion noise is discussed.

Combustion noise is typically measured by analysis of the in-cylinder pressure history recorded by a pressure sensor, because the noise measured by a microphone measures the combination of both the combustion noise and mechanical noise. **Figure 3** shows the procedure used for combustion noise measurements. First, a pressure trace on a time axis is developed by a Fourier series and is then converted to a frequency spectrum. The spectrum is first multiplied by a structural frequency filter, which simulates acoustic attenuation through an engine block, and is then multiplied by a so-called A-filter, which applies human acoustic characteristics. These steps generate the combustion noise spectrum that is emitted from the surface of the engine block. Then, the filtered frequency-domain spectrum is converted back into time-domain spectrum. Finally, the spectrum is normalized according to an acoustic reference of 20 μPa, and then integrated to output the overall combustion noise. Various combustion noise meters have been produced to date. The authors use AVL type 450 combustion noise meters.

It is well known that combustion noise is correlated

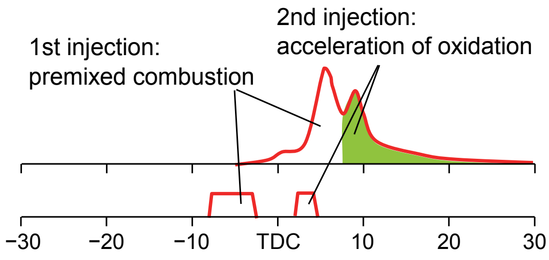

Fig. 2 Concept of PCCI combustion with split injection.

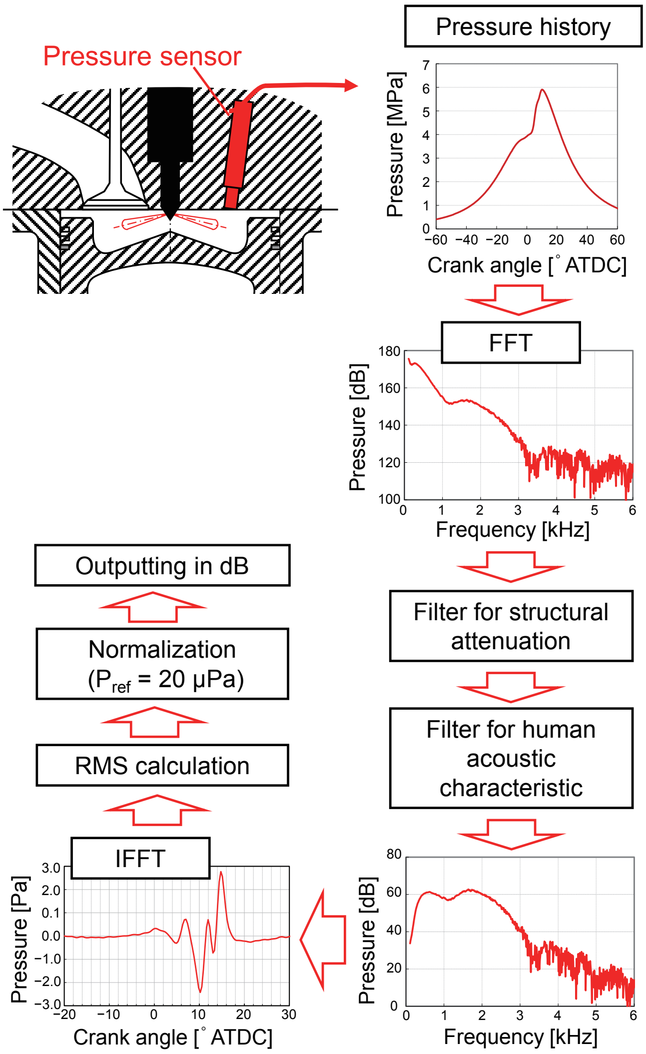

Fig. 3 Procedure of the combustion noise measurement based on pressure history analysis.

to $(dP/d\theta)_{max}$, which is the maximum of the in-cylinder pressure rise rate.(15,16) The noise has a strong correlation with $(dP/d\theta)_{max}$ especially in the case of PCCI combustion. There have been many reports on techniques to reduce PCCI combustion noise through a decrease in $(dP/d\theta)_{max}$ by control of factors such as the injection pattern, the supercharging boost rate, and the exhaust gas recirculation (EGR) rate.(15,17)

As another indicator of combustion noise, Eng proposed the ringing intensity (RI) to quantify the combustion noise caused by high frequency (4 to 8 kHz) pressure resonance, which appears as knocking in spark ignition (SI) engines.(18) The RI has been utilized to analyze the combustion noise in HCCI combustion, as well as the knocking.(19,20) The RI takes the effect of engine speed into account by using the time domain differential, $(dP/dt)_{max}$, in place of the crank angle domain differential, $(dP/d\theta)_{max}$. In addition, the RI involves the sound speed and pressure, and has units of MW/m^2, which indicates the quantitative work done by the pressure resonance on the combustion chamber wall.

3. Noise-canceling Spike Combustion

3. 1 PCCI Combustion with Split-injection

In PCCI combustion with a single injection, the amounts of unburned hydrocarbons (HC) and carbon monoxide (CO) are increased by advancing the injection timing. On the other hand, if the injection timing is retarded, the rate of heat release becomes very steep, and the combustion noise and the amount of NO_x emissions increase.(10) The authors have used split injection with control of each injection timing and the amount of fuel that is injected, thereby providing a combustion concept capable of significantly reducing emissions and combustion noise across a wide range of load/speed (Fig. 2).(10,11) This combustion concept has two features: premixed combustion of the first injected fuel, and accelerated oxidation of HC/CO by combustion of the second injected fuel. Timing the injection around top dead center (TDC) reduces the fuel consumption, and splitting the injection into two reduces the maximum heat release rate, which reduces the combustion noise.

Control of the second injection timing (interval between the first and second injections) and the amount of fuel that is injected are important factors to realize this concept. **Figure 4** shows the effects of the second injection timing on smoke and CO emissions, as well as combustion noise. **Table 1** lists the experimental conditions. Low smoke/CO emissions and further lowering of combustion noise can be achieved by optimization of the second injection timing.

Although the amounts of smoke, CO and combustion noise rapidly increase as a result of advancing or retarding the timing relative to the optimum timing of the second injection, the reason for this has not been explained.

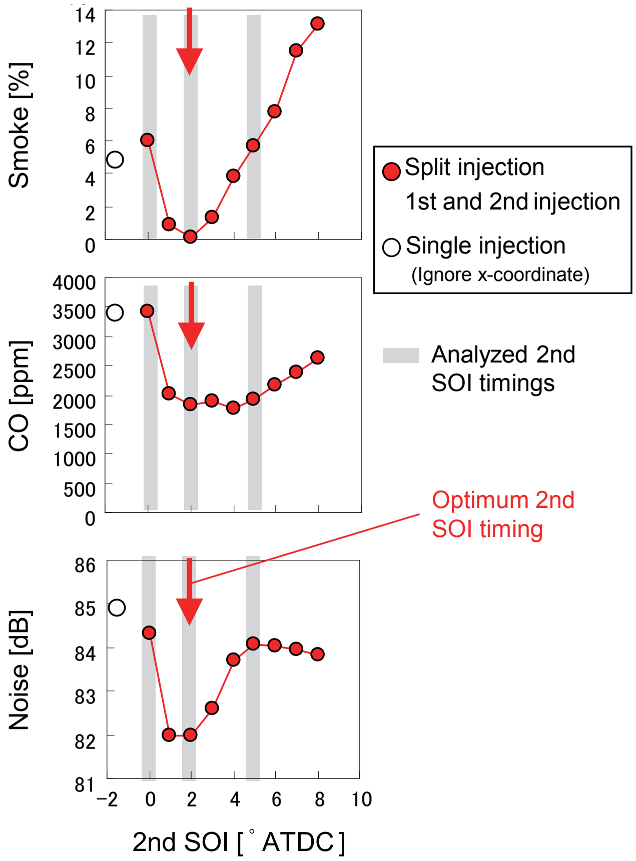

Fig. 4 Effects of timing of 2nd injection on smoke and CO emissions, as well as combustion noise.

Table 1 Experimental conditions.

Bore × stroke	86 × 86 mm
Swept volume	0.5 L
Comp. ratio	15.8
Nozzle	ϕ0.09 × 9, Piezo
Engine speed	1300 rpm
Inj. pressure	40 MPa
Inj. amount	10 + 5 mm^3/st
EGR rate	30%

The reason for the increase or decrease in the amount of smoke and CO, depending on the timing of the second injection, was revealed using both in-cylinder visualization and numerical simulations, the details of which are given in our previous paper.(11) **Figure 5** shows the in-cylinder pressure and heat release rate histories at three second injection timings, which are indicated by the gray bars in Fig. 4. One is the optimum timing at 2° after top dead center (ATDC), and the other two are an advanced timing TDC and retarded timing 5° ATDC, at which the combustion noise increases.

3. 2 Analysis of Pressure Rise Rate

Figure 6 shows a comparison of the $dP/d\theta$ histories and the combustion noise obtained from engine experiments. Although the $(dP/d\theta)_{\max}$ values are almost the same in the three cases of the second injection timing, the measured combustion noise is 2 dB lower in the case of 2° ATDC. Conventional engine combustion knowledge cannot explain this new phenomenon.

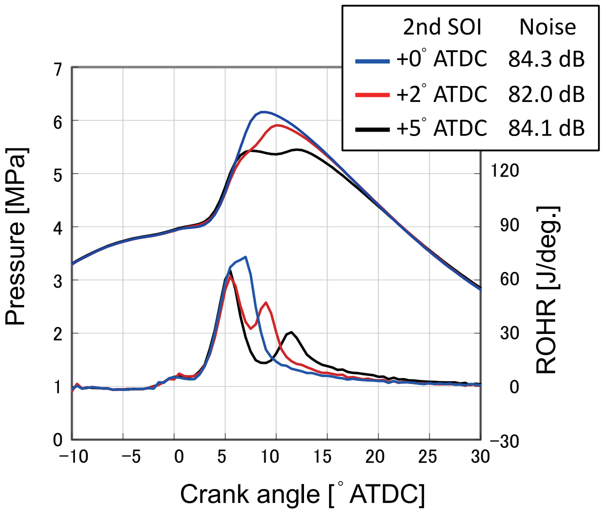

Fig. 5 Comparison of in-cylinder pressure and heat release rate at 1300 rpm.

A similar phenomenon that cannot be explained by the conventional knowledge was also found in an experiment carried out with a lower engine speed of 900 rpm (**Fig. 7**). The $(dP/d\theta)_{\max}$ values are almost the same for the second injection timings of 7.2° ATDC and 10° ATDC; however, the combustion noise is lower for 7.2° ATDC with a shorter injection interval.

These results (Figs. 6 and 7) suggest that interference occurs between the two pressure waves of the two heat release peaks produced by combustion of the first injected fuel and the second injected fuel. The combustion noise spectra obtained from the two engine operation conditions (1300 rpm, 900 rpm) were analyzed.

The RI was not used to quantify the combustion noise level, because the histories of pressure rise rate are smooth and without high-frequency vibration (Figs. 6 and 7). The combustion noise spectra show that the major frequency component is lower than 4 kHz (**Figs. 8** and **9**).

3. 3 Analysis of Combustion Noise Spectra

Figures 8 and 9 show the combustion noise spectra obtained under the two engine operation conditions. The noise spectrum from an ensemble average pressure trace was computed for 200 cycles. The sound pressure spectra shown in Figs. 8 and 9 have been passed through the two filters shown in Fig. 3. The sound pressure in

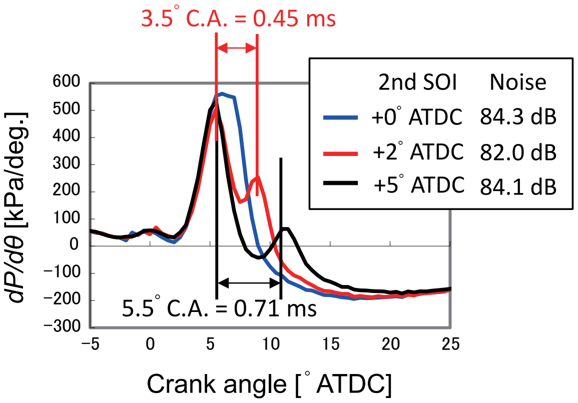

Fig. 6 Comparison of $dP/d\theta$ histories at 1300 rpm.

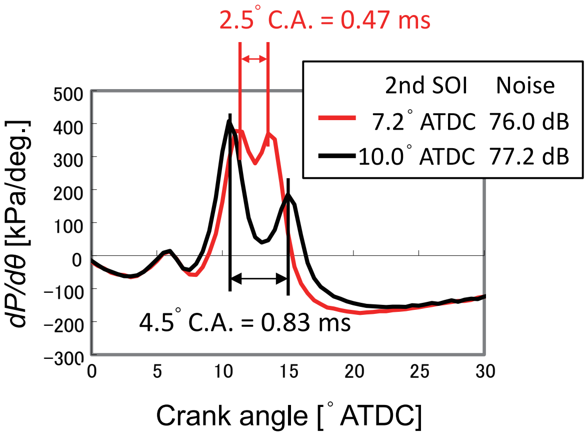

Fig. 7 Comparison of $dP/d\theta$ histories at 900 rpm.

decibels is logarithmic; therefore, the maximum value of this spectrum wave pattern mainly dominates the overall combustion noise.

Figure 8 shows the sound pressure spectra peak at approximately 67 dB, which is at a frequency of almost 1.1 kHz in the case of TDC injection and 5° ATDC injection, for which the overall combustion noise at operating speeds under 1300 rpm is high. Conversely, in the case of 2° ATDC injection, a valley appears around 1.1 kHz and pulls down the highest part of the combustion noise spectrum curve, which results in an overall combustion noise reduction of approximately 2 dB. For lower-speed operation (900 rpm, Fig. 9), the valley also appears around 1.05 kHz with injection at 7.2° ATDC. The valley pulls down the maximum value of the combustion spectrum curve, and thus the overall combustion noise is reduced.

The mechanism that causes the valley to appear was analyzed with a focus on the relationship between the *dP/dθ* peak interval and the center frequency of the valley. The case of the lower engine speed (Fig. 9) was analyzed first because the valley appeared clearly. In the case of 7.2° ATDC injection, the period of the valley center frequency at 1.05 kHz is converted to a time of 0.95 ms. This period is approximately two times 0.47 ms, which is the conversion of the peak interval crank-angle of 2.5°. This relationship, where the period is twice as long as the interval, reveals that the noise is reduced by the interference between the pressure waves. The frequency component (1.05 kHz) of the first *dP/dθ* peak interferes with the same frequency component (1.05 kHz) of the second *dP/dθ* peak. Both frequencies are the same but their phases are shifted by 1/2 of the period, such that the combustion noise is cancelled out. This relationship corresponds to the case of $n = 0$ for τ_n in the equation shown in **Fig. 10**.

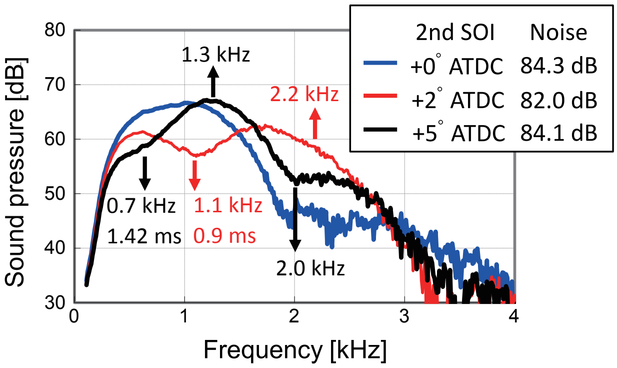

Fig. 8 Combustion noise spectra at 1300 rpm.

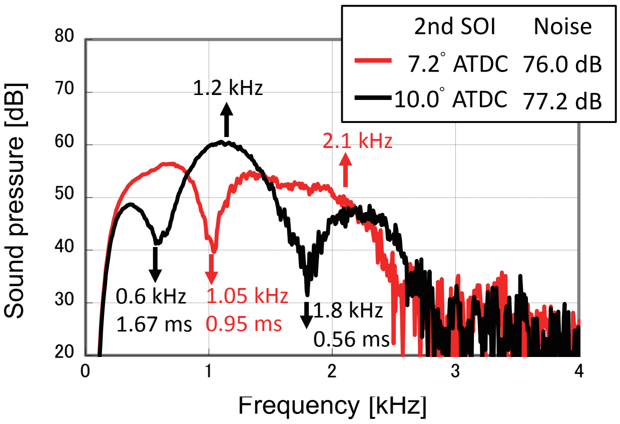

Fig. 9 Combustion noise spectra at 900 rpm.

In the case of injection at 10° ATDC with a longer injection interval, the spectrum curve exhibits more interesting features. The interval between the two *dP/dθ* peaks is 4.5°, which is converted to 0.83 ms. From the mechanism shown in Fig. 10 (a), a reduction in the frequency component is observed at a frequency

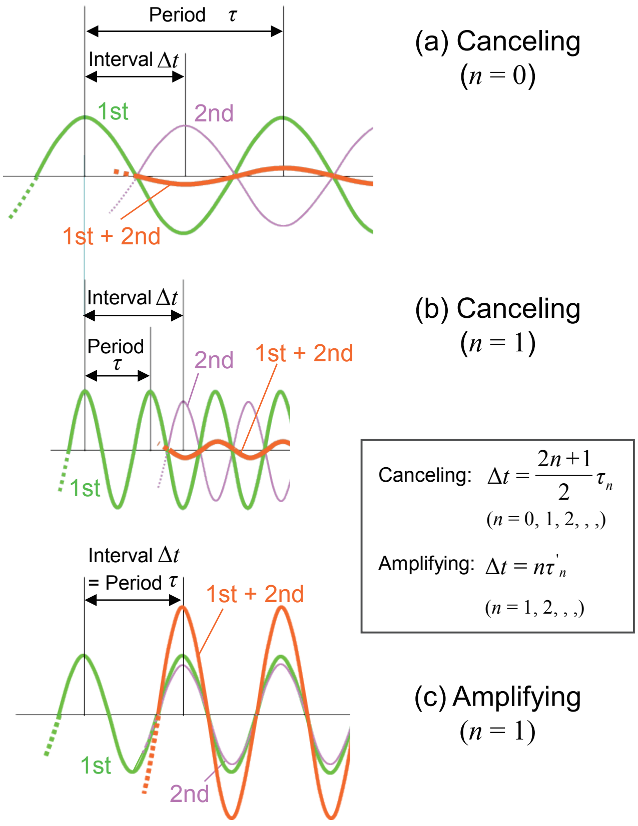

Fig. 10 Relation of the *dP/dθ* peak interval and the period of noise canceling/amplifying frequency.

of around 0.6 kHz, for which the period is twice the interval of the two $dP/d\theta$ peaks. Moreover, another valley also appears around 1.8 kHz, which is 2/3 of the interval between the two $dP/d\theta$ peaks. This relationship is illustrated in Fig. 10 (b) and corresponds to $n = 1$ for τ_n in the equation. Noise-canceling occurs at the frequency components around 0.6 and 1.8 kHz; however, the pressure waves can interfere at the frequency components around 1.2 kHz (their center) because the time period corresponds to the interval between the two $dP/d\theta$ peaks. The amplitude of the frequency component increases by the overlapping of these peaks, as shown in Fig. 10 (c). Therefore, the maximum value of the overall spectra around 1.2 kHz increases. This amplification case corresponds to $n = 1$ for τ_n' in the equation shown in the figure. For injection at 7.2° (Fig. 9, red line), where the frequency component is around 2.1 kHz, for which the period corresponds to the interval between the two $dP/d\theta$ peaks, the result is amplification. However, this amplification is not considered to contribute to the overall combustion noise, because the frequency component of 2.1 kHz is lower than the maximum value of around 1 kHz.

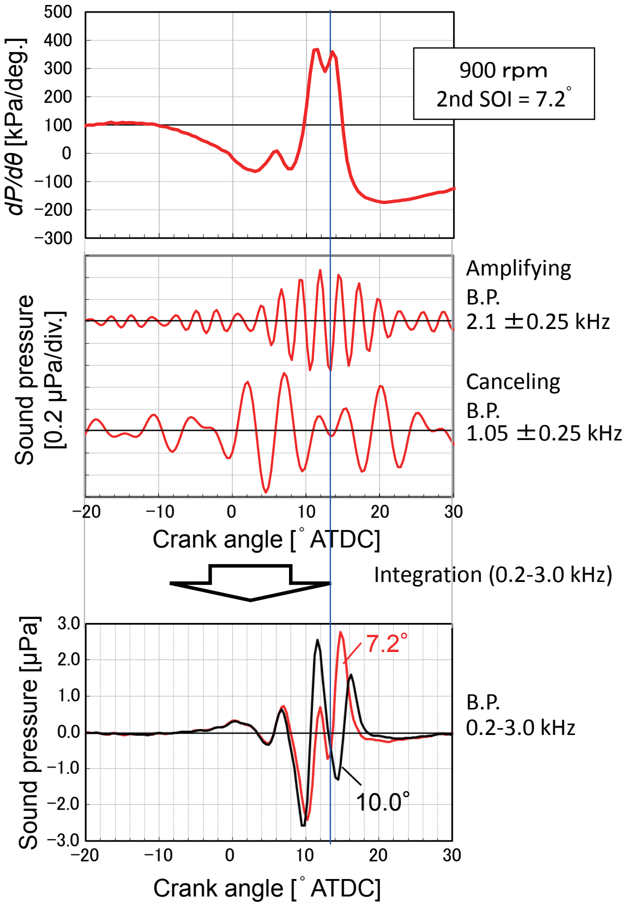

Fig. 11 Time-domain analysis of noise-canceling/amplifying at 900 rpm.

In addition to the frequency-domain analysis shown in Fig. 9, time-domain analysis of the interference (cancellation and amplification) of sound pressure waves was conducted for the lower engine speed of 900 rpm. **Figure 11** shows the histories of two sound pressure components together with the history of $dP/d\theta$; a 1.05 kHz component at which frequency canceling appears and 2.1 kHz component at which amplification appears. These components are extracted from pressure histories through bandpass filters (center frequency ±0.25 kHz). The blue vertical line shows the second $dP/d\theta$ peak 13.5° ATDC, where the wave amplitude of 1.05 kHz component is reduced to almost zero by canceling, while the wave amplitude of 2.1 kHz is almost a maximum by amplification. The lower panel of Fig. 11 shows the histories of sound pressure components over a wide frequency range from 0.3 to 3.0 kHz, in which the combustion noise spectra have high values. In the case of injection at 7.2° ATDC, the wave amplitude of the sound pressure wave becomes very small at the second $dP/d\theta$ peak of 13.5° ATDC. The wave amplitude increases again at 15° ATDC; however, the time domain-analysis (lower panel of Fig. 11) does not show the effects of noise-canceling so clearly as the frequency-domain analysis (Fig. 9). Therefore, the frequency-domain analysis (combustion noise spectra) is more feasible to explain the mechanism of noise-canceling.

Although the shape of the valley at 1300 rpm is not as clear as that at 900 rpm, the combustion noise spectra (Fig. 8) show the same tendency. For the longer interval obtained with injection at 5° ATDC (black line), the interval between the two $dP/d\theta$ peaks is 5.5°. Even though the frequency components of 0.7 and 2.0 kHz are reduced by canceling, the frequency components around 1.3 kHz are amplified; therefore, the maximum value of the spectrum is high. For the optimum injection timing of 2° ATDC (red line), the $dP/d\theta$ peak interval becomes 3.5°, which corresponds to an interval of 0.45 ms. A valley appears around the frequency component of 1.1 kHz in the spectrum in which the period is 0.9 ms. This valley pulls down the maximum value of the combustion noise spectrum, which reduces the overall combustion noise.

In the PCCI combustion concept with split injection, the combustion noise can be reduced primarily by decreasing $(dP/d\theta)_{max}$. Moreover, by setting an appropriate interval of $dP/d\theta$ peaks, further overall noise reduction can be realized by canceling the major noise frequency components. This noise reduction technique has been termed noise-canceling spike combustion because it relies on interference between a spike in the pressure rise with the preceding pressure rise peak.

4. Discussion

The principle of the interference/canceling between pressure waves utilized in noise-canceling spike combustion is the same principle of the widely used noise-canceling technique. In the field of audio devices, noise-canceling headphones have become widespread. The noise-canceling used for audio devices is broad-banded noise-canceling for the wide frequency range audible to humans, emitting sound waves with an inverted phase (1/2 period shifted) from a speaker. On the other hand, noise-canceling in a cylinder of a diesel engine proposed here can be classified into narrow-banded noise-canceling, which appears at discrete frequencies for which the period is twice or 2/3 times the interval of the $dP/d\theta$ peaks. Each $dP/d\theta$ peak hits the wall of the cylinder like a bell hammer and emits pressure waves for a wide frequency range. The phase of the major pressure waves is dominated by the timing of the $dP/d\theta$ peak.

This noise-canceling between the two $dP/d\theta$ peaks can occur under different conditions, as determined from our investigations. While the fuel amount of the second injection was smaller than that of the first injection in this study, the noise-canceling spike can occur when the fuel amount of the 1st injection is smaller than that of the 2nd injection. After the authors' presentation of noise-canceling spike combustion, Shibata et al. studied the effects of the 1st and 2nd injection fuel amount ratio on the noise-canceling spike in PCCI combustion using zero-dimensional simulations and single-cylinder engine tests.(21) They showed that the effect of the noise-canceling spike becomes a maximum when the 1st and 2nd injection fuel amount ratio is 35:45. Thus, as long as two $dP/d\theta$ peaks appear with an adequate interval, the noise-canceling spike can occur.

The noise-canceling spike can also occur in conventional diesel combustion with multi-injection. The authors have confirmed through combustion spectral analysis that the noise-canceling spike occurs between the $dP/d\theta$ peaks of the pilot and main combustion when the amount of the main injection is relatively so small that the main combustion forms a clear $dP/d\theta$ peak. Busch et al. measured combustion noise from diesel combustion with the pilot-main injection strategy in a single cylinder engine and found that a combustion noise decrease appears with a short injection interval, which is approximately 3 dB below the level obtained with longer intervals.(22) They also applied the frequency-domain analysis; however, they could not find a relationship between the interval of the $dP/d\theta$ peaks and the valleys of the spectra caused by the noise-canceling, shown by Figs. 8-10 in this paper, because the $dP/d\theta$ profile of the main combustion is very complicated and has 3 or 4 peaks. The authors consider that the noise-canceling spike is one of the factors that caused the noise reduction in the experiments reported by Busch et al.(23,24)

5. Summary

Combustion noise spectra analysis was used to clarify the combustion noise reduction mechanism by optimization of the second injection timing (injection interval) for PCCI combustion with split injection. Noise-canceling occurs between the two peaks in the pressure rise rate at the optimal second injection timing, which reduces the overall combustion noise by reducing the maximum frequency component of the noise spectrum. The authors have termed this noise reduction phenomenon noise-canceling spike combustion. The maximum load range for conventional PCCI combustion is limited by the combustion noise because the maximum pressure rise rate increases with the amount of fuel being injected. Noise-canceling spike combustion has the potential to extend the operating range of PCCI combustion. In addition, noise-canceling spike combustion can occur between two heat releases of the pilot and main injection fuels in diesel combustion with multi-injection.

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Figs. 2-10
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Takayuki Fuyuto
Research Field:
- Engine Combustion

Academic Societies:
- The Japan Society of Mechanical Engineers
- Society of Automotive Engineers of Japan
- Combustion Society of Japan

Awards:
- Outstanding Presentation Award, JSAE, 2011
- Outstanding Technical Paper Award, JSAE, 2009 and 2013
- Encouragement Award, Combustion Society of Japan, 2009

Masahiro Taki
Research Field:
- Internal Combustion Engine

Academic Society:
- Society of Automotive Engineers of Japan

Awards:
- A. T. Colwell Merit Award, SAE, 1985
- Outstanding Technical Paper Award, JSAE, 1986

Hiroshi Kuzuyama*
Research Field:
- Engine Combustion

Academic Societies:
- Society of Automotive Engineers of Japan
- The Japan Society of Mechanical Engineers

Award:
- Outstanding Technical Paper Award, JSAE, 2012

Tsutomu Umehara*
Research Fields:
- Engine Combustion
- Engine System

Academic Society:
- Society of Automotive Engineers of Japan

Award:
- Outstanding Technical Paper Award, JSAE, 2013

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