Technique to Enhance Engine Combustion Sound Quality in Passenger Compartments at the Early Stage of Vehicle Development

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ABSTRACT: This paper discusses a technique for the examination of countermeasures at the early stage of vehicle development to realize efficient enhancement of the engine combustion noise quality. The key point of this technique is to utilize the existing combustion noise quality evaluation method as a simulation technology at the design stage of development. By doing this, the necessary measures can be estimated using the in-cylinder pressures of the newly developed engine measured on the bench and the structure response functions obtained from the previous mass-production vehicle. This process was applied to the new Kei car development and the results demonstrated the effectiveness of above technique.

KEY WORDS: Vibration, noise, and ride comfort, Idling vibration/idling noise/acceleration noise, Test and analysis technology / Combustion noise, Sound quality, Simulation, Vehicle development process [B3]

1. Introduction

Increasing the quietness of the vehicle interior is an important factor in increasing the commercial appeal of automobiles. As evidenced by descriptions of the noise as rumbling, rattling or knocking, the acceptability of the engine combustion noise produced during acceleration is influenced not only by the sound pressure level of the noise, but also by its quality. Because of this, there are cases in which the auditory impression cannot be enhanced even though the sound pressure level of the noise has been reduced using some measures.

In order to address this issue, the authors developed a new sound quality assessment method by combining the time domain combustion noise separation method (T-CNSM) with the dissonant combustion noise index (DCNI)⁽¹⁾. The former noise separation method has made it possible to extract only the components contributed by in-cylinder pressure (termed “combustion noise” below) from vehicle interior noise during acceleration in an audible form, and the latter index has made it possible to accurately quantify the sound quality of combustion noise. The use of this method has enabled the setting of numerical targets for the sound quality of combustion noise in the initial stages of complete vehicle development, and, following completion of the prototype vehicle, to quantitatively determine the degree of achievement of the target and efficiently judge the necessity or lack of necessity for further sound quality measures.

However, automotive development today is required to reduce both the period from planning to start of mass production and the prototyping costs. Therefore, it is necessary to obtain a prospect for the realization of combustion noise quality targets before the stage of completion of the prototype vehicle. This is because large-scale design changes following the completion of the prototype vehicle necessitate a considerable amount of development reworking. At the same time, the realization of enhanced combustion noise sound

quality is antagonistic to the realization of increased fuel efficiency and reduced vehicle weight, and it is therefore desirable to attempt to avoid reflecting excessive countermeasures in the drawings.

Accordingly, the authors considered a development process in which the application of countermeasures for combustion noise, which have often been applied after the completion of the prototype vehicle in conventional developments, could be applied at the prototype vehicle design stage by using the sound quality assessment method discussed above as a simulation technology.

The research discussed in this paper applied this development process in the development of a new Kei car fitted with a newly developed engine designed on the basis of a rapid combustion concept in order to enhance fuel economy. As a result, it was possible to realize the interior combustion noise quality targets in the initial prototype vehicle using countermeasures examined in the design phase. Following this, there was no need to introduce further countermeasures prior to the stage of verification for mass production. The new process allowed countermeasures for combustion noise sound quality to be introduced in a shorter period and more efficiently than in the conventional process.

This paper provides an overview of the development process described above, and discusses the results of the application of the process in an actual new Kei car development and the achieved outcomes.

2. Overview of Objective Evaluation Method for Combustion noise quality

This chapter will provide an overview of the developed objective evaluation method, which represents an important analytic tool in increasing the efficiency of the examination of measures addressing the sound quality of combustion noise. This method was developed by combining the time domain combustion noise separation method (T-CNSM) with a sound quality

evaluation index tailored to combustion noise, the dissonant combustion noise index (DCNI)⁽¹⁾.

2.1. Time Domain Combustion Noise Separation Method

The time domain combustion noise separation method (T-CNSM) makes it possible to extract combustion noise from actually measured noise during acceleration in the time domain. The analytic procedures are as follows:

- [i] Measure vehicle interior noise and in-cylinder pressures of each cylinder simultaneously during acceleration
- [ii] Extract the contribution of combustion noise in the time domain from the measured data [i] via digital signal processing using Fourier transforms and multiple regression analyses.

The tests for [i] are conducted using a chassis dynamometer in a semi-anechoic chamber. As shown in Figure 1, in-cylinder pressure sensors are fitted in all cylinders, and an artificial head microphone is positioned in the passenger seat to measure interior noise. These are input to the PAK multi-channel measurement and analysis system manufactured by Muller-BBM, and measurements are conducted simultaneously. In this case, the sampling frequency is set at 16,384 Hz, with the upper limit for frequency set at 4,400 Hz, taking in-cylinder pressure measuring accuracy into account.

On chassis-dynamometer in semi-anechoic chamber

Figure 1 Measurement apparatus

Next, the signal processing described in [ii] is conducted. Combustion noise $spc(n\Delta t)$ for an arbitrary discrete time $n\Delta t$ is calculated from the measured data obtained in [i] using Eq. (1) (* means a convolution operation). The structural response function $h_k(n\Delta t)$ is calculated statistically in the frequency domain using multiple regression analysis.

$$spc(nT) = \sum_{k=1}^N h_k(n\Delta t) * cp_k(n\Delta t) \quad (1)$$

- Δt : Sampling period
 N : Number of cylinders
 $spc(n\Delta t)$: Combustion noise
 $cp_k(n\Delta t)$: Cylinder pressure of each cylinder
 $h_k(n\Delta t)$: Structural response function from each cylinder to evaluation point

2.2. Dissonant Combustion Noise Index

The sound quality of combustion noise $spc(nT)$ obtained using T-CNSM is quantified for each interval of approximately 0.1 seconds using the objective evaluation index DCNI. As indicated by Eq. (2), the DCNI can be calculated from a psychoacoustic metric: fluctuation intensity (unit: mon)^(2,3,4) at each Bark scale critical band in Table 1⁽⁵⁾. Fluctuation intensity makes it possible to quantify the unpleasantness of perceived fluctuation for amplitude-modulated noise such as rumbling, rattling, or knocking, which cannot be expressed by conventional noise evaluation scales such as an A-weighted sound pressure level.

$$DCNI = \sum_{z=3}^{18} Fluctuation\ intensity\ (z) \quad (2)$$

- z : Bark scale critical band

Table 1 Bark scale critical band⁽⁵⁾

Bark number	Center frequency (Hz)	Cut-off frequency (Hz)	Bandwidth (Hz)
		20	
1	60	100	80
2	150	200	100
3	250	300	100
4	350	400	100
5	450	510	110
6	570	630	120
7	700	770	140
8	840	920	150
9	1,000	1,080	160
10	1,170	1,270	190
11	1,370	1,480	210
12	1,600	1,720	240
13	1,850	2,000	280
14	2,150	2,320	320
15	2,500	2,700	380
16	2,900	3,150	450
17	3,400	3,700	550
18	4,000	4,400	700
19	4,800	5,300	900
20	5,800	6,400	1,100
21	7,000	7,700	1,300
22	8,500	9,500	1,800
23	10,500	12,000	2,500
24	13,500	15,500	3,500

Using the method described above, it is possible to obtain a quantitative understanding of the vehicle interior sound quality due to combustion noise.

3. Proposal of Development Process that Front-loads Measures to Enhance Combustion Noise Quality in Vehicle Interior

Large-scale countermeasures against the deterioration of combustion noise quality have often been applied at a later stage of conventional vehicle development. In response to this issue, the authors proposed a new development process for front-loading these countermeasures to initial design phase. Figure 2 compares the flow of (a) the conventional process, and (b) the proposed process.

Figure 2 Comparison of conventional process and proposed process for development of combustion noise countermeasures

"Objective evaluation" in Fig. 2 refers to analysis using the combustion noise quality evaluation method discussed in the preceding chapter. While there is no difference between (a) and (b) in terms of the use of objective evaluation in addition to subjective evaluation in the examination of combustion noise countermeasures, in the case of (b), the objective evaluation method is applied as a simulation technology, and is used from the design study stage of the initial prototype vehicle. By focusing efforts on the examination of countermeasures at the design stage,

the aim is to reduce the number of countermeasures applied following the completion of the prototype vehicle, and thus to complete the application of combustion noise quality countermeasures more efficiently and in a shorter period. An overview of the proposed process shown in Fig. 2(b) is provided below.

First, in the target-setting phase, benchmark and other tests are conducted, and numerical targets for the sound quality of combustion noise in vehicle interior are set using the DCNI, in addition to targets set using conventional subjective evaluation. These procedures are the same as for the process shown in (a).

Tests are conducted in advance, and measured data are obtained. These data are the structural response functions of the previous mass production model and the in-cylinder pressure of a newly developed engine which will be intended for use in new vehicles. Afterward, signal processing based on Eq. (1) is conducted using these measured data. The change in the DCNI, if the new engine was fitted in the previous model, is predicted and the need for additional countermeasures is judged. If it has been judged that countermeasures are necessary, the frequency bands that represent the weak point for sound quality are identified, and the response sensitivity of the structural response functions of the previous mass production model is arbitrarily varied, allowing estimation of the minimum necessary reduction in the response sensitivity that makes it possible to satisfy the DCNI target. This makes it possible to identify the degree to which measures are to be applied to the structural system in order to realize the DCNI target.

Following this, based on the degree of reduction in response sensitivity obtained from the simulation discussed above, specific countermeasures are examined, with the focus divided into engine components and body components. The proposed countermeasures that can be expected to have an effect on the sound quality of combustion noise are selected and incorporated in the initial drawings for the prototype vehicle. In this phase, some of the countermeasures incorporated in the later stages of the conventional development would be front-loaded to the design of the initial prototype vehicle.

The procedure from completion of the initial prototype vehicle to the commencement stage of mass production is the same as that in the conventional process shown in Fig. 2(a). However, it can be predicted that the degree of target achievement in the initial prototype vehicle will be greater than in the conventional process due to the measures incorporated in the initial drawings, and that any additional countermeasures applied later would be small-scale.

4. Example of Application of Proposed Process

The combustion noise countermeasure development process proposed in the previous chapter (Fig. 2(b)) was applied in the development of the 2017 model of a Kei car for the Japanese market, and its effectiveness was verified. This chapter first offers an overview of the developed vehicle, following which it looks at the development process in time series from target-setting to verification of the mass production vehicle, following the flow shown in Fig. 2(b).

4.1. Overview of Developed Vehicle

This section provides an overview of the new model Kei car ("the new model" below). The goal for the new model was to increase fuel efficiency and dynamic performance against the 2013 model, and to also achieve a high level balance of those performances, comfort, and quietness. In relation to the major goal of increasing fuel efficiency, in addition to the application of comprehensive measures to reduce weight throughout the vehicle, a new engine was used in which the basic structure had been overhauled in order to increase thermal efficiency⁽⁶⁾.

Table 2 compares the main specifications of the engines in the new model and the previous model, and Fig. 3 compares the engine power characteristics. The thick black lines in Fig. 3 show figures for the new model, while the fine orange lines show figures for the previous model.

Table 2 Specifications of engines

	New model	Previous model
Cylinder layout	Inline-3	Inline-3
Air intake	Natural aspirated	Natural aspirated
Valvetrain	DOHC with Intake VTC & VTEC	DOHC with Intake VTC
Displacement	658 cm ³	658 cm ³
Bore x stroke	60 x 77.6 mm	64 x 68.2 mm
Stroke / bore ratio	1.29	1.07
Compression ratio	12.0	11.8
Max power	43 kW (7300 rpm)	43 kW (7300 rpm)
Max torque	65 Nm (4700 rpm)	65 Nm (4700 rpm)

Figure 3 Comparisons of engine power and torque

As Table 2 indicates, the stroke is longer in the engine used in the new model, and the compression ratio has been increased. In addition, in order to reduce time loss, the shapes of the intake ports and the combustion chamber were modified, increasing turbulence energy and allowing the realization of rapid combustion. While it increases thermal efficiency, the use of a longer stroke also presents the issue of reducing power at high engine speeds. In response to this issue, in addition to the variable valve timing control (VTC) mechanism that continuously controlled the phase of the intake valves in the previous model, a variable valve timing and lift

control (VTEC) mechanism⁽⁷⁾ that varies the degree of valve lift was also used in the new model. As Fig. 3 shows, this measure made it possible for the engine used in the new model to equal or exceed the power and torque of the previous engine.

4.2. Setting Targets for Combustion Noise Quality in New Model

Comparative subjective evaluations for combustion noise quality were conducted in driving tests using a previous model and several competitors' vehicles. The specifications of their powertrains were 0.66 l natural aspirated inline-3 gasoline engine with the continuously variable transmission (CVT). Based on the results of the subjective evaluations, combustion noise quality target for the new model was set at the same auditory feeling level of the previous model.

Figure 4 shows the numeric target of combustion noise quality for the new model based on objective evaluations. The horizontal axis shows engine speed, and the vertical axis shows the DCNI based on Eq. (2). The combustion noise quality level in the vehicle interior of the previous model is shown as the orange line. The experiment was conducted on the chassis dynamometer in an anechoic chamber as shown in Fig. 1, and the operating conditions were acceleration from 2,000 to 6,000 rpm under full load in the D (drive) shift position. The required time was approximately 7.5 seconds as shown in Fig. 5, and the vehicle speed increased at a constant gradient from 5 to 65 km/h. This condition is consistent with a rapid acceleration phase, such as entering a highway from a general road in Kei car class vehicles, and in this condition the combustion noise quality deterioration usually becomes most noticeable.

Taking into consideration the results of the subjective evaluations, the DCNI target level for the new model was set at the same level as the previous model, shown as the black broken line in Fig. 4.

Figure 4 Target-setting for combustion noise quality in vehicle interior under full load acceleration

Figure 5 Engine speed under full load acceleration in time domain

4.3. Simulation using Measured Data

4.3.1 Effect of Combustion Characteristic of New Engine

The newly developed engine, discussed above, used rapid combustion in order to increase fuel efficiency, and there was concern that this would result in a decline in the sound quality of combustion noise. Therefore, a simulation was performed to predict how much the combustion noise quality would deteriorate if the engine developed for the new model were to be fitted in the body of the previous model.

Specifically, as shown in Figure 6, a digital signal processing based on Eq. (1) was conducted using measured data. Those data were the in-cylinder pressures measured in dynamometer bench tests during the advanced development of the new engine and the structural response functions for the previous model measured in chassis dynamometer tests. It was assumed that only the characteristics of the in-cylinder pressures in the previous model would be replaced by those of the newly developed engine.

$$spc(nT) = \sum_{k=1}^N h_k(nT) * cp_k(nT)$$

↑
Previous model
New engine

Vehicle test
Engine bench test

Figure 6 Method of prediction of combustion noise in interior of developed vehicle based on assumption that newly developed engine is installed

Figure 7 Influence of in-cylinder pressure on sound quality in newly developed engine under full load acceleration

Figure 7 shows the results of sound quality evaluation of simulated combustion noise using the DCNI. The axes of this graph are the same as in Figure 4. The broken pink line shows the simulated combustion noise. The simulated combustion noise DCNI is higher than that for the previous model, and in the 4,000 rpm and below operating range the DCNI exceeds the target by two times or more. In addition, when the authors listened to this combustion noise on a specialized audio-playback system (HEAD acoustics, PEQ-V), it was found that in the range of 4,000 rpm and below, the noise was not only louder, there was also conspicuous rattling or knocking noise that caused discomfort.

In order to clarify the cause of this, a detailed analysis of changes in the in-cylinder pressure characteristic was conducted. The results are shown in Figure 8. The solid orange line shows in-cylinder pressure for the previous mass production model, while the broken pink line shows in-cylinder pressure for the new engine obtained in a dynamometer bench test during the advanced development.

(a) Rate of increase in in-cylinder pressure

(b) Frequency spectrum

Figure 8 Comparison of in-cylinder pressure characteristic for #1 cylinder under full load

Figure 8(a) shows a comparison of the maximum value of the rate of increase ($dP/d\theta_{max}$) in in-cylinder pressure P for each crankshaft angle θ in cylinder #1 for the engines used in the new model and the previous model. The horizontal axis shows engine speed, and the vertical axis shows the maximum value of the rate of increase in in-cylinder pressure. Combustion in the engine for

the new model is rapid as intended, and there is a maximum increase of 0.05 MPa/deg. in $dP/d\theta_{max}$.

Figure 8(b) shows a comparison of in-cylinder pressure in cylinder #1 on the frequency axis for the 2,500-4,000 rpm range in which the increase in DCNI is conspicuous. The vertical axis shows the in-cylinder pressure level. The difference between the two sets of figures becomes conspicuous at 1,500 Hz and above, and at 2,000 Hz and above, the in-cylinder pressure level in the new engine is 8 dB or more higher than the previous engine. These results indicate that the cause of the increase in the DCNI in the 4,000 rpm and below range for the combustion noise simulated using in-cylinder pressure for the new engine, shown in Fig. 7, is an increase in the high-frequency component of in-cylinder pressure as a result of the use of rapid combustion.

4.3.2 Specification of Frequencies causing Decline in Sound Quality

In the preceding section, it was indicated that the combustion characteristic of the new engine would cause a deterioration in sound quality. However, the application of measures affecting combustion, such as retardation of ignition timing, would be directly related to declines in power and fuel efficiency. Therefore, it was decided to apply measures for only structural systems to realize the target sound quality of combustion noise. First, before the examination of concrete proposals, the frequency band to be targeted was identified.

Because, based on Eq. (2), the DCNI is the sum of the fluctuation intensities in the 3-18 Bark, the frequency bands that represent the issue can be identified by dividing the fluctuation intensity in each critical band. Figure 9 shows a color contour diagram of the results of a fluctuation intensity analysis of the predicted combustion noise shown as broken pink lines in Fig. 7. The horizontal axis shows engine speed, and the vertical axis shows the critical band. Colors show fluctuation intensity. Focusing on the area 4,000 rpm and below, fluctuation intensities in the 6 Bark (510-630 Hz), 10-12 Bark (1,080-1,780 Hz), and 15 Bark (2,320-2,700 Hz) bands stand out as the highest.

Figure 9 Fluctuation intensity of simulated combustion noise in vehicle interior

Figure 10 Structural response functions for previous model

Figure 10 shows the structural response functions for the previous model. The structural response functions indicate the transfer characteristics from each cylinder to an artificial head microphone positioned in the vehicle interior. The structural response function characteristic differs between the right and left ears of the artificial head. The structural response functions from the cylinders to the left ear of the artificial head are shown here as a representative example. In addition, although the structure response functions in Equation (1) mean the impulse responses, they are shown as the frequency response functions in Fig. 10 using a Bode diagram in order to make it easier to understand their characteristics in the frequency domain. The horizontal axes of the two graphs show frequency, while the vertical axis of the top graph shows phase, and the vertical axis of the bottom graph shows response sensitivity (unit: Pa/Pa). The response function from each cylinder to the left ear of the artificial head is shown as differing colors. In addition, the three cylinders' response amplitude power additional value is shown at +5 dB offset with black line as a reference in order to grasp the overall sensitivity trends. Peaks in the previous model's structural response functions occurred at 0.6, 1.2, 1.4, 1.6 and 2.5 kHz, and these correspond well with the frequency bands in which fluctuation intensity was highest in Fig. 9.

Figure 11 shows the results of a comparison of spectrograms of combustion noise at the left ear of the artificial head. Figure 11(a) shows combustion noise for the previous model, while Fig. 11(b) shows combustion noise simulated using in-cylinder pressures of new engine. The horizontal axes for each graph show frequency and the vertical axes show engine speed. Colors show the A-weighted sound pressure level.

Figure 11 Comparison of spectrogram of combustion noise at the left ear microphone of artificial head

The areas surrounded by broken white lines are the operating conditions and frequency bands for which fluctuation intensity was highest in Fig. 9. Comparing combustion noise in Figs. 11(a) and (b) with a focus on these areas shows that in the case of 11(b), in addition to the sound pressure level of combustion noise being higher, the contiguous frequency spectra are also denser. This tendency is particularly marked in the case of the frequency bands centering on 0.6, 1.2, 1.4, 1.6 and 2.5 kHz, in which the structural response sensitivity peaks occurred in Fig. 10. These were considered to be the origin of the uncomfortable fluctuating sound. It was therefore thought that if it were possible to reduce the peaks of structural response sensitivity, it would be possible to make the fluctuating sound less noticeable and reduce the DCNI.

4.3.3. Identification of Level of Reduction in Structural Response Sensitivity Necessary for Achievement of Sound Quality Targets

In the previous section, the authors showed that the combustion characteristics of the new engine would cause the sound quality to deteriorate. Therefore, it was necessary to consider using countermeasures to maintain the sound quality. However, countermeasures that involved combustion control, such as retarding the ignition timing, would directly lead to the degradation of engine output and fuel consumption. Therefore, the authors decided to achieve the target sound quality by making only structural modifications.

Before considering specific countermeasures, other simulations were conducted based on the analysis results discussed in the previous section, in order to predict how much structural response sensitivity should be reduced by changing the structural system in order to achieve the DCNI targets. The following method was used. First, based on the structural response functions for the previous model shown in Fig. 10, the modified structural response function $h'_k(nT)$ was created, reducing only response sensitivity centering on the peak frequency bands, without changing phase. Next, as shown in Fig. 12, combustion noise $spc'(nT)$, following the change in the structural response function, was calculated based on the modified structural response function $h'_k(nT)$ and the in-cylinder pressure of the new engine, $cp_k(nT)$, which was used in the predictive calculations, and the results of which are shown in Fig. 6, with the degree of reduction in the DCNI in Eq. (2) determined. This process was repeated until the DCNI targets shown in Fig. 4 were achieved, making it possible to estimate the minimum necessary reduction level in the structural response sensitivity in each frequency band for achievement of the DCNI targets.

$$spc'(nT) = \sum_{k=1}^N h'_k(nT) * cp_k(nT)$$

↑ ↑
Modified New engine
Engine bench test

Figure 12 Method of predicting change in combustion noise due to change in structural response functions

Figure 13 Modifications of response sensitivities of structural response functions

The results are shown in Fig. 13. Response sensitivity was reduced by a maximum of 10 dB before the peaks occurring at 0.6, 1.2, 1.4, 1.6 and 2.5 kHz were flattened and the solid black line showing the three cylinder's response amplitude power additional value fell below the guideline, shown as a broken line; in the high frequency band of 2 kHz and above, the reduction in response sensitivity was a uniform 3 dB. The DCNI for combustion noise obtained using these structural response functions is shown as the thick navy blue line in Fig. 14. It is clear that the structural response functions in Fig. 13 made it possible to largely achieve the DCNI targets.

Based on the simulation results discussed above, the solid black line in Fig. 13 was set as the target level for structural response sensitivity, and the structural system countermeasures necessary for achieving this target line were examined.

Figure 14 Prediction of enhancement of combustion noise quality by modification of structural response functions

4.4. Examination of Specifications of Initial Prototype Vehicle

Concrete countermeasures proposed for the engine and the vehicle body were examined based on the reduction in response sensitivity for each frequency shown in Fig. 13. Primary verification of the effectiveness of proposed countermeasures for components of the engine was conducted using the prototype engine on an engine acoustic test bench. Similarly, primary verification of the effectiveness of countermeasures for components of the vehicle body was conducted using the previous mass production vehicle in an anechoic chamber. In addition, only measures that were expected to be effective in ameliorating combustion noise were rigorously selected from the test results, and incorporated in the initial prototype vehicle drawings. Figure 15 provides an overview of the measures.

Figure 15 Measures for enhancement of combustion noise quality

Measures for engine components were studied separately for structure-borne system and airborne noise system. Regarding structure-borne system, the mount bracket resonance frequency was increased from 600 Hz to 800 Hz by the modification of the bracket shape. Regarding the airborne system, peaks of response sensitivity at 600 Hz, 1.2-1.6 kHz and 2.5 kHz were reduced, which had been caused by resonances of head cover, the oil pan and the

front cover. It was achieved by changing shape of the parts, making flat parts curved and increasing the thickness of parts without exceeding the weight targets for each part.

Regarding the measures for components of the vehicle body, reducing the area of the opening of the dash panel insulator, increasing the thickness of the insulator in the engine compartment, and reducing the area of the opening between the engine chamber and the cabin were studied in order to reduce acoustic sensitivity from the engine chamber to the cabin. Figure 16 shows the results of primary verification of the effects of these measures in speaker excitation tests using the mass production vehicle. The horizontal axis shows frequency, and the vertical axis shows acoustic sensitivity from the engine chamber to the microphone in the cabin. The orange line shows the baseline for the previous model, and the thick black line shows the characteristics of the vehicle following the implementation of the measures described above. These measures realized a reduction of 5 dB or more in acoustic sensitivity in the high-frequency band of 1 kHz and above.

Figure 16 Comparison of acoustic sensitivity from engine compartment to vehicle interior

4.5. Verification of Combustion Noise Sound Quality in Initial Prototype Vehicle

Figure 17 shows the comparison of the engine speed under full load acceleration in the time domain. The thick black line shows the engine speed of the initial prototype. The increasing rate of the engine speed versus the time is different between the previous model and the initial prototype, because the engine power, as shown in Fig. 3, and the CVT control setting were modified in the initial prototype. However, the required time for acceleration from 2,000 to 6,000 rpm in the initial prototype was approximately 7.5 seconds and the vehicle speed increased at a constant gradient from 5 to 65 km/h, as in the previous model.

The thick black line in Fig. 18 shows the DCNI for the initial prototype vehicle, in which the countermeasures shown in Fig. 15 were reflected. The axes of the graph are the same as those in Fig. 4. The combustion noise sound quality in the initial prototype vehicle exceeds the DCNI target by approximately 15% at 4,500 and 5,500 rpm, but overall realizes the same level as in the previous model. In fact, when the sound quality of combustion noise in the previous model and the prototype vehicle were subjected to a comparative subjective evaluation in a driving test, the decline in sound quality at 4,500 and 5,500 rpm was found to be minor in

terms of the auditory sensation, and the vehicles were verified as realizing the same level.

Figure 17 Comparison of engine speed under full load acceleration in time domain

Figure 18 Level of achievement of combustion noise sound quality in initial prototype vehicle

Figure 19 Spectrogram of combustion noise in vehicle interior of initial prototype vehicle

Figure 19 shows a spectrogram of combustion noise in the cabin of the initial prototype vehicle. In the domains that represented an issue, surrounded by broken white lines, not only has the sound pressure level been reduced in comparison with Fig. 11(b), but the conspicuous frequency spectra have also been reduced.

Finally, to provide a reference, Fig. 20(a) shows a comparison of the in-cylinder pressure level in the previous model and the initial prototype vehicle, and Fig. 20(b) shows a comparison of the

response sensitivity of the structural response function. The axes are the same as those for Fig. 8(b) and Fig. 10. The orange line shows results for the previous model, and the black line shows results for the initial prototype vehicle.

(a) #1 cylinder pressure level

(b) Structural response function

Figure 20 Comparisons of cylinder pressure level and structural response function

The in-cylinder pressure level in the initial prototype vehicle shown in Fig. 20(a) is the same as that in the advanced development of the new engine in Fig. 8(b). The components at 1.5 kHz and above are 8 dB or higher than in the previous model. However, the response sensitivity of the initial prototype vehicle shown in Fig. 20(b) shows no conspicuous peaks exceeding the guidelines except at 1.4 kHz. In addition, there was a reduction of 10 dB or more in the band at 2.5 kHz and above, representing a higher-than-anticipated reduction in response sensitivity. Based on the results shown in Figs. 18 and 20, the decline in the sound quality of combustion noise that represented a concern with the realization of more rapid engine combustion has been offset in accordance with the target by the application of measures in the structural system

that were able to be examined in the design phase.

4.6. Combustion Noise Measures up to Commencement of Mass Production

Because the sound quality targets for combustion noise were achieved in the initial prototype vehicle, there was no need for additional countermeasures. The issue in the later stage of development was simply to check that design changes to the structural system due to other performance demands did not result in a decline in the sound quality of combustion noise. Following this, there were no design changes or modifications of combustion control to enhance combustion noise, and development of this new mass-produced Kei car model was completed smoothly.

5. Discussion

Because it was not possible to complete combustion noise countermeasures in the initial design phase in the conventional vehicle development process, the level of achievement of targets usually tended to be low in the initial prototype vehicle. Given this, it was necessary to apply large-scale countermeasures in the later stage of the development process, increasing the time and man-hours necessary for examining such measures.

By contrast, in the Kei car development discussed in this paper, a simulation was used to narrow down the measures necessary to achieve the combustion noise quality targets in the design phase for the initial prototype vehicle, and these were incorporated into the initial drawings. While there was a certain increase in the man-hours necessary for examination of countermeasures in the design phase, the achievement of the targets in the initial prototype vehicle did away with the need to expend any further time or man hours on further countermeasures in the later development process. This result has reaffirmed the importance of completing the examination of countermeasures in the design phase to the realization of efficient product development.

In addition, this development also indicated that increasing the level of achievement of combustion noise targets in the initial prototype vehicle is important to the ability to realize a high level balance against combustion noise, fuel efficiency, and vehicle weight reduction. In past vehicle developments, it has sometimes been the case that it has not been possible to achieve combustion noise quality targets until the final stage of development, when there is virtually zero degree of freedom in changing the structural design, and it has been necessary to respond with additional measures such as retardation of ignition timing or the addition of mass in a manner that is not weight-efficient and nullifies the effect of weight reductions, which unavoidably reduce power and fuel efficiency. In the Kei car development discussed in this paper, it was not necessary to apply countermeasures of this kind; the application of countermeasures for combustion noise was smoothly completed with the incorporation of structural system countermeasures in the initial drawings. To provide a reference, the new mass-produced Kei car realizes a level of quietness equivalent to or higher than the previous model, while also increasing fuel efficiency by 1.4 km/l in Japanese JC-08 mode and reducing the weight of the vehicle by 60 kg.

6. Conclusion

- (1) In order to realize efficient combustion noise quality enhancement, a new development process was proposed that front-loads the application of effective countermeasures to the design stage of initial prototype vehicle. The key point of this process is to utilize the existing combustion noise quality assessment method as a simulation technology at the design stage of vehicle development. The procedure is as follows.
 - [a] Set the numerical target for combustion noise quality in the vehicle interior using the dissonant combustion noise index.
 - [b] Estimate the deterioration of combustion noise quality using the in-cylinder pressures of the newly developed engine measured on an engine test bench and the structural response functions measured on a previous mass-production vehicle.
 - [c] Estimate the response sensitivity reduction level of the structural system for each frequency band to achieve the target of [a], taking into consideration the results of [b].
 - [d] Examine countermeasures for the engine unit and the vehicle body based on the result of [c].
 - [e] Reflect the countermeasures proposed in [d] in the initial design drawings of the prototype vehicle.
- (2) The new development process described in (1) was applied in the development of new Japanese Kei car equipped with a newly developed engine, which was designed based on the concept of realizing rapid combustion in order to increase fuel efficiency. As a result, the target combustion noise quality was achieved in the initial prototype vehicle, and that made it possible to eliminate additional measures in the subsequent development stages. In addition, it was possible to complete combustion noise quality enhancement in a shorter period than in the conventional development process. These results demonstrate that the new development process is effective in enhancing the efficiency of vehicle development.

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