

Prediction Technology of Output Power and Intake-Exhaust Noise Using 1D-Simulation for Small-Displacement Motorcycles

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ABSTRACT

Using a 1D simulation that transforms the 3D shape of intake-exhaust systems into one dimension and calculates the thermodynamics and fluid gas dynamics of internal combustion engines, a prediction technology of the output power and intake-exhaust noise for small-displacement single-cylinder motorcycles was established. Output power can be calculated accurately for various engines with different displacements and cooling systems by adjusting the boundary conditions in the calculation model. The intake-exhaust noise can be calculated accurately by clarifying some important points for accuracy when transforming the 3D shapes of the intake-exhaust system into the 1D model and by reflecting them in the calculation model. As for mufflers that have complicated internal structures, the calculation of exhaust noise cannot be made with sufficient accuracy because 1D simulation does not calculate spatial flow behavior. But, enhancement of accuracy is expected using a 1D-3D coupled simulation.

1. Introduction

Nowadays, reduction of noise from motorcycles is becoming increasingly important in Southeast Asian countries, the main market for small-displacement motorcycles. It takes a lot of time to decide the specifications of their engines and intake-exhaust systems in mass production development, because the shapes of the intake-exhaust systems are complex due to limited space in the layout. Usually, in the development of a new model, the specifications of the engine and intake-exhaust system are designed using various methods^{(1), (2)}. These methods specialize in either output power calculation or intake-exhaust noise calculation, and it is a challenge to evaluate the influence on output power and intake-exhaust noise coincidentally when specifications are changed. As a result, specifications are often decided by repeating experiments using a prototype vehicle. Therefore, there has been a demand for the development of a prediction technology that can calculate both output power and intake-exhaust noise coincidentally in initial stages of development.

1D simulation is one solution to this issue. A higher level modeling approach is required for 1D simulation

to calculate the output power and intake-exhaust noise accurately at the same time. While studies of 1D simulation for automobiles and large-displacement multi-cylinder motorcycles have been reported in the past⁽³⁾⁻⁽⁵⁾, there are no systematic studies found on the intake-exhaust system and single-cylinder engines for small-displacement motorcycles. A prediction technology that allows the calculation of both output power and intake-exhaust noise coincidentally for motorcycles with small-displacement single-cylinder engines using 1D simulation has been developed.

2. Simulation Method

2.1. 1D Simulation

In this study, WAVE[®], a 1D simulation analysis software manufactured by RICARDO plc, was used⁽⁶⁾. This 1D simulation calculates the dynamic behaviors of a working fluid by discretizing and solving basic equations such as the mass conservation law, Navier-Stokes equation, energy conservation law, and gas state equation after transforming the 3D shapes of the intake-exhaust system into a 1D shape.

1D simulation enables the calculation of output power

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and pressures in the intake-exhaust system. Moreover, sound waves that propagate to the surrounding space (i.e., intake-exhaust noise) can be calculated using flow velocity at the open end of intake-exhaust system.

2.2. Calculation Model

There are some factors that affect calculation accuracy in a 1D simulation. Representative factors are as follows:

- (1) The accuracy of numerical values given as input conditions, such as port discharge coefficients and mechanical friction losses.
- (2) The accuracy of boundary conditions related to heat transfer such as the inner surface temperatures of pipes and cylinders.
- (3) Modeling techniques that transform three-dimensional shapes such as duct length, duct diameter, and volume into the 1D shape.

Since the influence of these factors changes depending on engine type and load conditions, sufficient consideration is needed to consistently obtain a higher calculation accuracy under various conditions. Figure 1 shows an example of a calculation model. The range of the calculation model is all pipes and volumes from the opening of the intake duct in the air cleaner to the tail pipe end in the muffler, and the engine cylinder.

The main input conditions and boundary conditions used for calculation are as follows:

- The discharge coefficients of the intake-exhaust port are based on data that are measured with the test rig on steady flow.

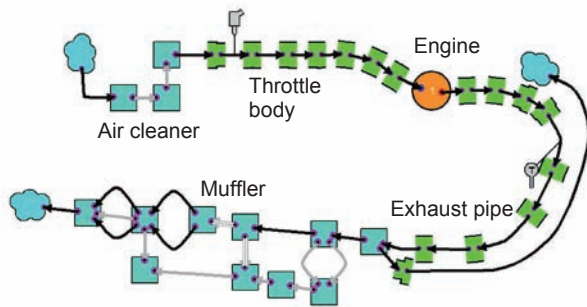


Fig. 1 Calculation model

- As mechanical friction losses, the data that subtract pumping losses calculated by a 1D simulation from the total friction losses measured by the motoring friction method are used.
- As a heat release by combustion, the Wiebe function with adjusted parameters to correspond to the measured heat release rate is used
- The inner wall temperature of the intake pipe is based on measured data, and the wall temperatures of the cylinder and exhaust pipe are based on appropriate values referring to past measured values.

3. Verification of Calculation Accuracy

3.1. Test Motorcycles

Table 1 shows the major specifications of the engine and intake-exhaust system of the test motorcycles used for verification. Each engine has a two-valve layout, and electronically-controlled fuel injection systems. The only major differences of engine specifications are the engine displacement and the cooling system. On the other hand, the intake-exhaust systems are different in each test motorcycle. For example, Test Motorcycle (C) has a complex curved intake duct as shown in Fig. 2, and Test Motorcycle (B) has a U-shaped, curved pipe in the muffler as show in Fig. 3. These are typical examples of arranging components efficiently in the limited space with small-displacement motorcycles.

3.2. Output power

The output power of the test motorcycles was measured using a dynamometer under full load conditions. Figure 4 shows a comparison of the measured and calculated output power and torque. The calculated result corresponds most closely with the measured result in the case of Test Motorcycle (A), which has an air-cooled engine. The calculation error is only around 2%, and the characteristics of the output power curve also correspond closely to the measured result. In the case of Test Motorcycle (B), which has a water-cooled engine, the calculated result is lower than the measured result when using the same boundary conditions as Test Motorcycle (A). The calculated volumetric efficiency is also lower than

Table 1 Specification of motorcycles used for verification

Test motorcycles	A	B	C
Engine type	4-stroke single cylinder	4-stroke single cylinder	4-stroke single cylinder
Cooling system	Air-cooled	Water-cooled	Air-cooled
Displacement (cm ³)	150	125	110
Valve layout	IN: 1 / EX: 1	IN: 1 / EX: 1	IN: 1 / EX: 1
Ignition type	Spark ignition	Spark ignition	Spark ignition
Air cleaner volume (L)	2.6	3.7	2.3
Muffler volume (L)	4.7	3.6	2.2
Muffler structure	3-pass	3-pass	3-pass

the measured result, so the boundary conditions were adjusted for Test Motorcycle (B). As a result, sufficient accuracy of calculation is obtained. Thus, it was found that it is necessary to set differing boundary conditions for water-cooled and air-cooled engines. In the case of Test Motorcycle (C), there is a slight error between the measured and calculated result at lower engine speeds. However, the measured and calculated characteristics of the output power curve correspond almost exactly, so it can be said that there is sufficient accuracy for practical use.

In order to confirm the validity of the input conditions and boundary conditions, accuracy validation was carried out adding another four test motorcycles with different

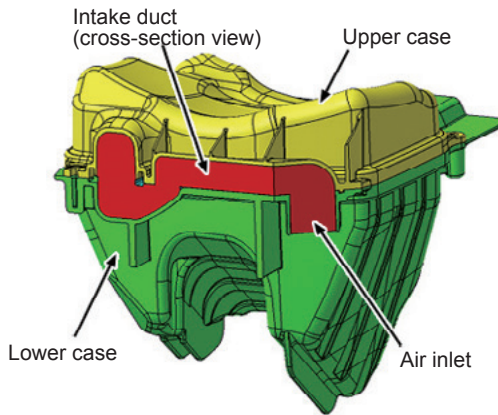


Fig. 2 Intake duct of test motorcycle (C)

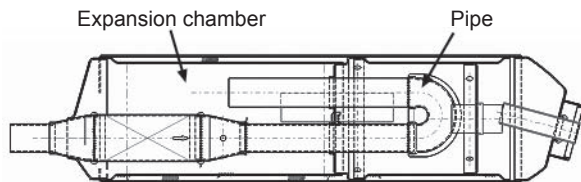


Fig. 3 Structure of muffler of test motorcycle (B)

engine displacements and cooling systems. Like the results of Test Motorcycles A, B, and C, there are very few calculation errors.

Figure 5 shows the correlation between measured and calculated results for maximum output power for all test motorcycles. The gradient of the approximation curve and the coefficients of correlation are each approximately 1, and this indicates that a higher calculation accuracy is obtained. From these results, it was found that a 1D simulation can calculate the output power with sufficient accuracy for most small-displacement single-cylinder motorcycles.

Next, the calculation accuracy of the indicated work was verified. Test Motorcycle (A) and (B) were verified, with a measurement engine speed of 6000 r/min which generated maximum torque under full load conditions. Figure 6 shows a comparison of P-V diagrams for measurement and calculation. As the diagrams show, the pumping loss in the charging strokes and the exhaust strokes correspond closely. In addition, the transition of in-cylinder pressure at the

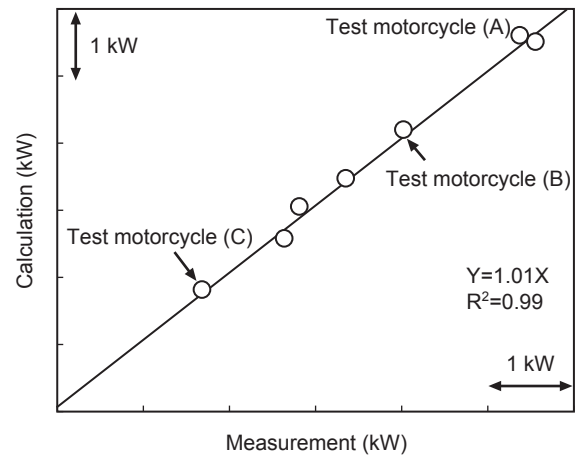


Fig. 5 Comparison of measured and calculated maximum output power

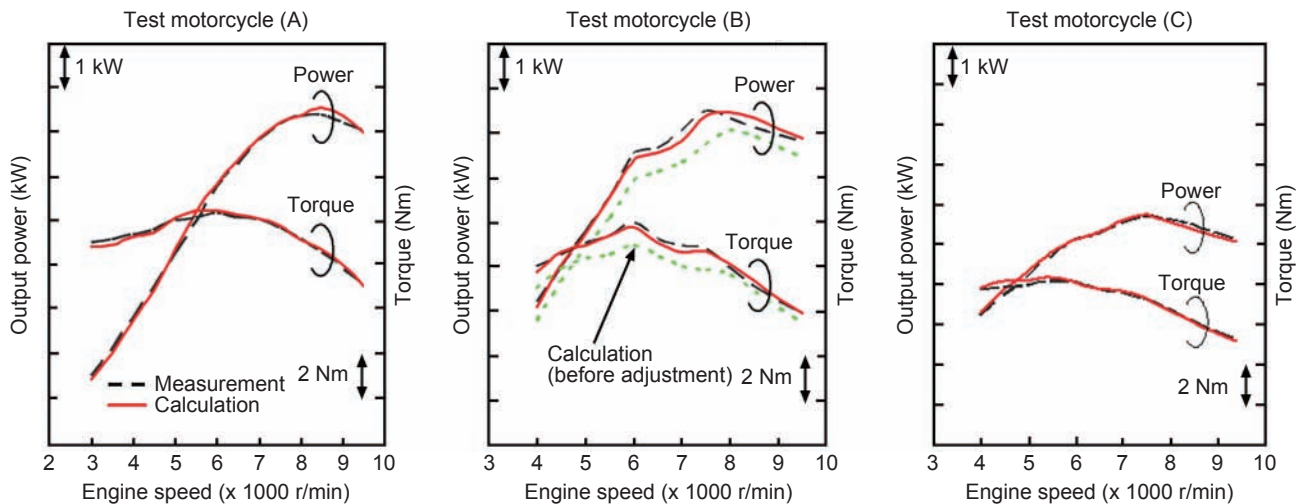


Fig. 4 Comparison of measured and calculated output power and torque

compression strokes and the expansion strokes, maximum pressure, and the timing of maximum pressure also correspond almost closely. This proves that the volumetric efficiency, heat release by combustion, and cooling losses for the cylinder wall are calculated accurately.

Next, it was verified whether these models can calculate changes of output power when the specifications of the exhaust systems were modified. The modifying point of specification was exhaust pipe length upstream of the catalyst.

Figure 7 shows the measured and calculated output power characteristics. Figure 8 shows the rate of output power change. The measured results indicate that output power increases at lower engine speeds and decreases at higher engine speeds when the exhaust pipe length upstream of the catalyst becomes longer, and the opposite when the exhaust pipe length upstream of the catalyst becomes shorter. The calculated results show the same tendencies, and the results for the rate of output power change are similar to the measured results. Thus, it was confirmed that these calculation models could also calculate output power accurately even when the exhaust system specifications are modified.

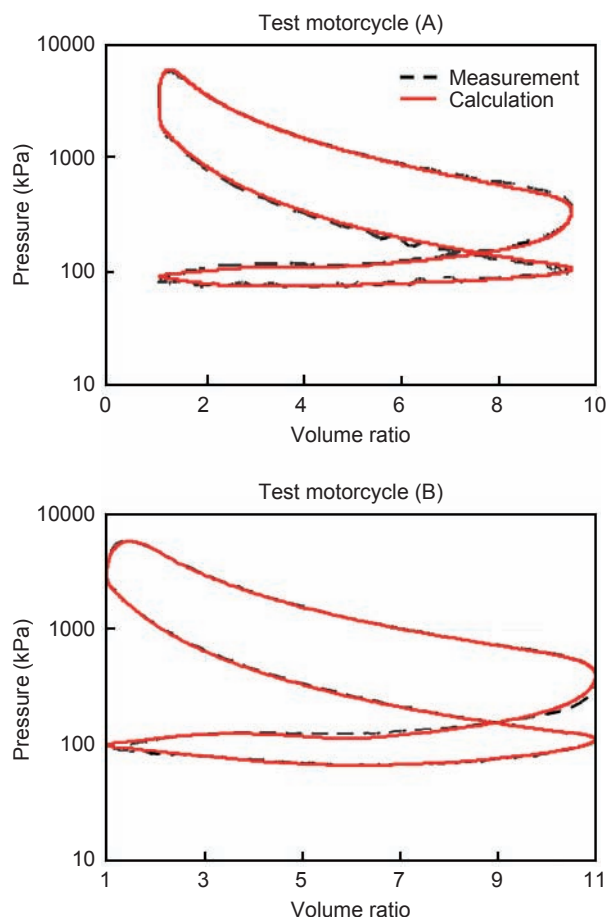


Fig. 6 Comparison of measured and calculated P-V diagram

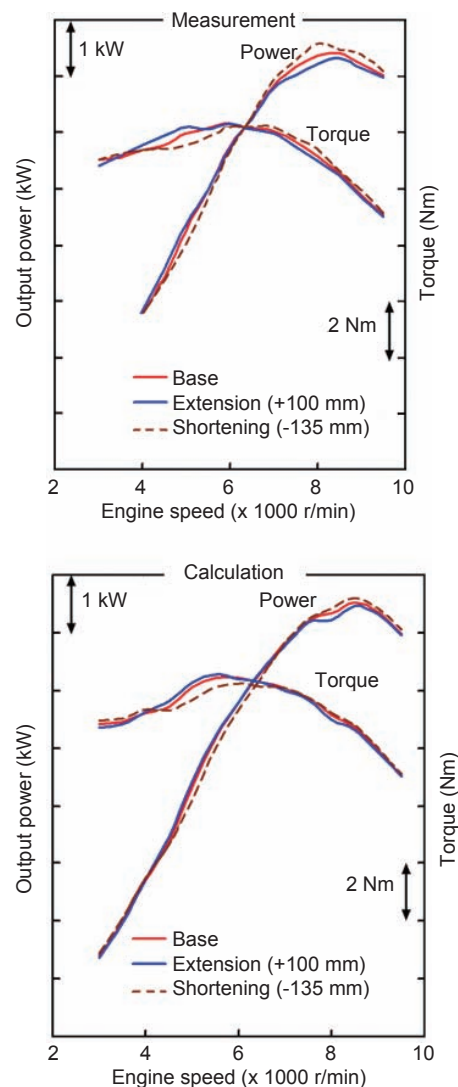


Fig. 7 Comparison of measured and calculated output power and torque when changing exhaust pipe length

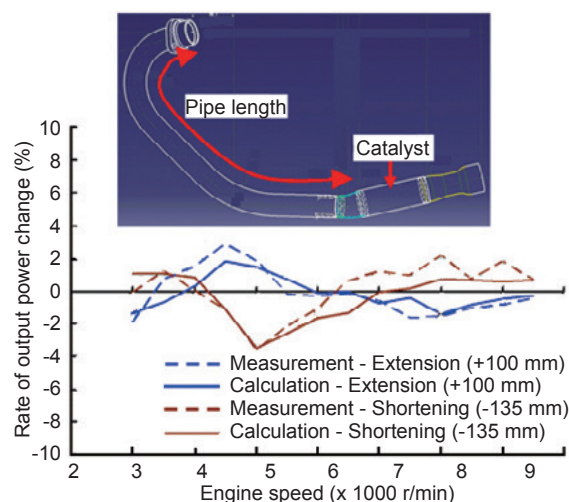


Fig. 8 Rate of output power change when changing exhaust pipe length

3.3. Intake-exhaust Noise

The calculation accuracy of intake-exhaust noise was verified using Test Motorcycle (A), (B), and (C). Table 2 shows measurement and calculation conditions. The intake-exhaust noise was measured at the engine speed where the sound pressure level indicates maximum value in pass-by noise measurements. Intake noise was measured inside the intake duct by a pressure sensor, and exhaust noise was measured near the tail pipe by a microphone. By measuring at such places, noises other than the intake-exhaust pulsation noise, (e.g., the shell noise of the air cleaner box, the mechanical noise inside the engine), were reduced as much as possible. The verified frequency domain was up to 500 Hz for both intake noise and exhaust noise, because the sound pressure level in this domain contributed greatly to the overall sound pressure level. In the criteria for accurate calculation of the intake-exhaust noise, it was assumed that the measured and calculated results were in the same tendency concerning the sound pressure level of each order components in the frequency analysis. In addition, the pressure of time domain near the intake and exhaust valves was measured at the same time as measuring the intake-exhaust noise. By evaluating them in those positions, the calculation accuracy of the pressure waves that are regarded as the source of intake-exhaust noise were verified indirectly.

3.3.1. Intake noise

Figure 9 shows a comparison of the measured and calculated frequency analysis result and overall sound pressure level of intake noise. For the intake noise, Test Motorcycle (A) and (B) show favorable correlations between measurement and calculation. But, for Test Motorcycle (C), the calculated sound pressure level was higher than the measured one, especially below the 100 Hz frequency domains. Figure 10 shows the pressure near the intake valve. The measured and calculated results correspond well for Test Motorcycle (A), (B) and (C). Therefore, it was thought that the sound transfer function

could not be calculated accurately for Test Motorcycle (C) because the 1D modeling of the intake system had been inadequate.

Then, the element that was thought to have a large influence on sound transfer function was clarified, and the input shape and size were reviewed in the calculation model. Figure 11 shows a comparison of the measured intake noise and that calculated with the modified model of Test Motorcycle (C). The calculated sound pressure level lower than 100 Hz in the frequency analysis is enhanced, so a favorable correlation can be confirmed.

3.3.2. Exhaust noise

Figure 12 shows a comparison of the measured and calculated frequency analysis result and overall sound pressure level of exhaust noise. Test Motorcycle (A) and (B) show a favorable correlation between measurement and calculation. However, in case of Test Motorcycle (C), the calculated sound pressure level is much lower

Table 2 Measurement and calculation conditions of intake-exhaust noise

Load condition	Full load
Operation condition	Steady state
Throttle condition	Wide-open throttle
Measured engine speed	At Max. sound pressure level in pass-by noise measurement
Measurement position	Inside intake duct (Intake noise)
	Near tail pipe opening (Exhaust noise)
Analysis method	Frequency analysis
Frequency range	0 - 500 Hz
Frequency resolution	4 Hz
Window function	Hanning

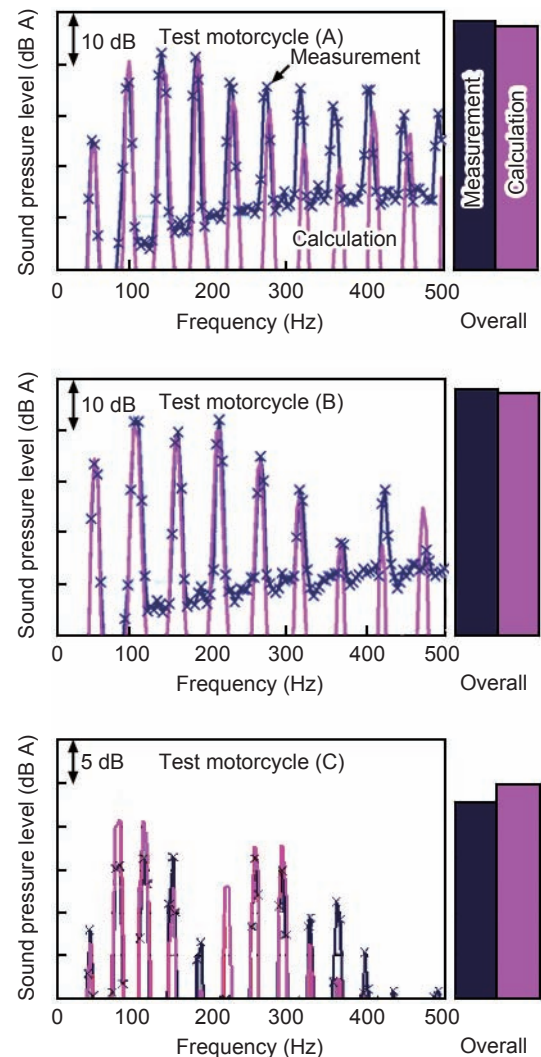


Fig. 9 Comparison of measured and calculated intake noise inside intake duct

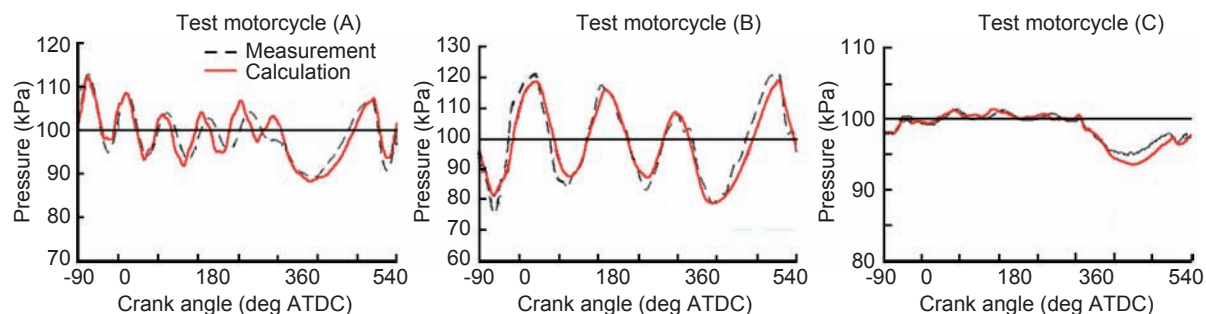


Fig. 10 Comparison of measured and calculated pressure wave near intake valve

than the measured one at frequencies over 200 Hz, so the correlation between measurement and calculation is not sufficient.

Figure 13 shows the pressure near the exhaust valve. As in the case of the pressure near the intake valve, measured and calculated results correspond well for all test motorcycles. Therefore, it was considered that the 1D modeling of the area downstream from the exhaust pipe was inadequate for Test Motorcycle (C).

Figure 14 shows the internal structure of the muffler of Test Motorcycle (C). Comparing the differences of internal structure between the mufflers of Test Motorcycle (A) and (B), which have higher calculation accuracy, and that of Test Motorcycle (C), it was found that the distance between the exhaust pipe and inner pipe is closer and the central axes of both pipes are almost coaxial in Test Motorcycle (C). It was assumed that these characteristics are the main reason for the decreased calculation accuracy of exhaust noise for Test Motorcycle (C). In order to verify this assumption, the single-chamber mufflers shown in Fig. 15 were made. These mufflers have the same chamber volume, pipe length and diameter, while the relative dimensions of the central axes between the exhaust pipe and inner pipe are different from each other. Figure 16 shows a comparison of the measured and calculated exhaust noise for both mufflers.

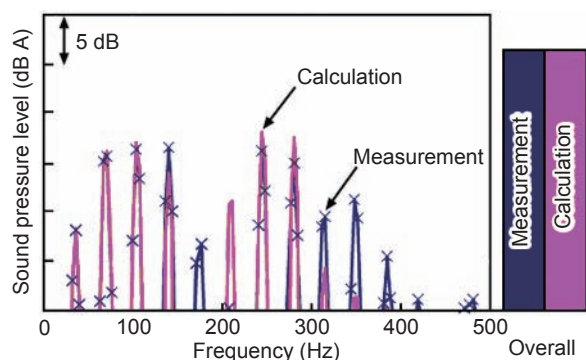


Fig. 11 Comparison of measured intake-noise inside intake duct and that calculated with modified model of test motorcycle (C)

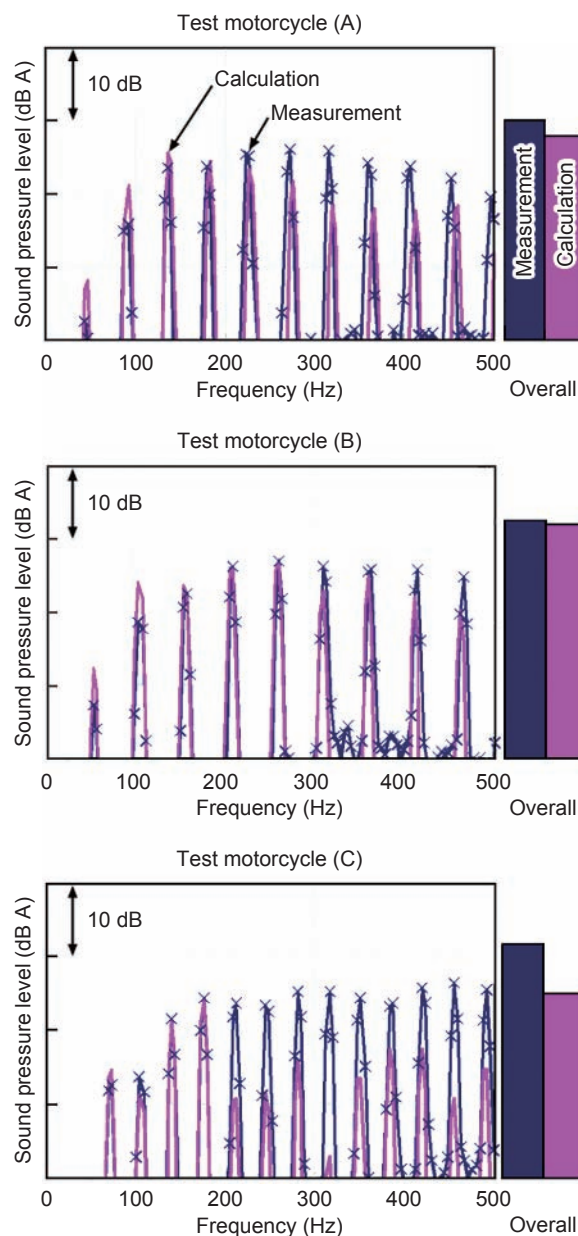


Fig. 12 Comparison of measured and calculated exhaust noise

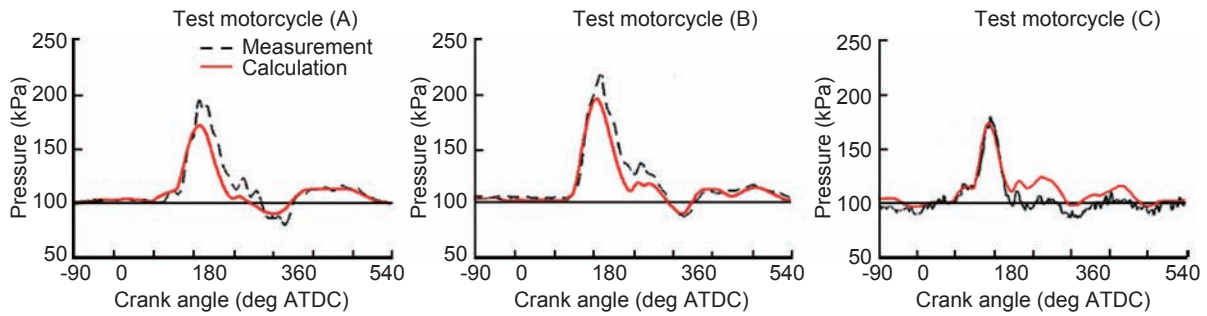


Fig. 13 Comparison of measured and calculated pressure wave near exhaust valve

When the central axes of the exhaust pipe and the inner pipe in the muffler are coaxial (“coaxial configuration” below), the calculated results are lower than the measured result for all frequency domains. At higher frequencies in particular, the differences are more than 20 dB. On the other hand, a favorable correlation can be confirmed when each pipe is not in a coaxial configuration. Considering these results, it was found that a 1D simulation could calculate exhaust noise as long as each pipe is not in a coaxial configuration, and that sufficient calculation accuracy is not obtained using a 1D simulation alone if each pipe is coaxial configuration.

It is known that calculation accuracy in a 1D simulation can be enhanced by discretizing the volume section of the muffler in detail. But, the calculation accuracy had not been enhanced in this verification though detail discretization was done.

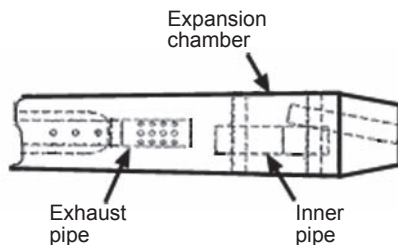


Fig. 14 Structure of muffler of test motorcycle (C)

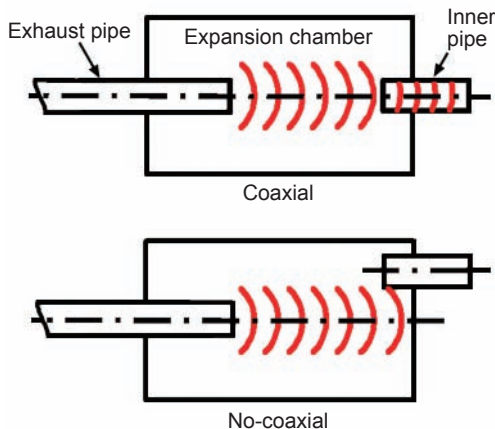


Fig. 15 Structure of single-chamber mufflers

3.4. Approach for Enhancing Calculation Accuracy of Exhaust Noise by Applying a 1D-3D Coupled Simulation

For the mufflers that the exhaust pipe and the inner pipe are in a coaxial configuration, it was estimated that the reason that the measured result was higher than the calculated result is that the emission gas actually run through the next pipe without sufficient expansion in the expansion chamber. In order to re-create this phenomenon using a 1D simulation, verification was executed with single-chamber mufflers. However, the calculation accuracy could not be adequately enhanced. Then it was verified whether the calculation accuracy could be enhanced by

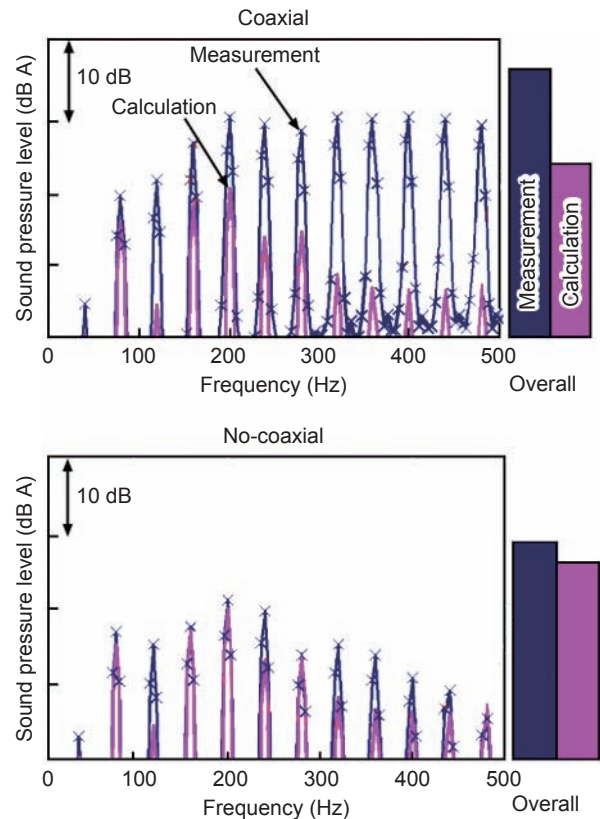


Fig. 16 Comparison of measured and calculated exhaust noise for different pipe positions

coupling a 1D simulation with a 3D simulation (“1D-3D Coupled Simulation” below). 1D-3D coupled simulation is executed by alternately transferring data on pressure, flow velocity, gas temperature and so on, at the connecting point. The software used for the 3D simulation was VECTIS, a commercial 3D thermo and fluid dynamics analysis software made by Ricardo Plc⁽⁷⁾.

Figure 17 shows multi-chamber mufflers. Three different mufflers were made. In the first one, the exhaust pipe and inner pipe are in a coaxial configuration (Type 1); in the second, they are partly in a coaxial configuration (Type 2); and in the third, they are not in a coaxial configuration (Type 3). For all mufflers, the measured and calculated exhaust noise was compared. Figure 18 shows the 3D simulation model. The scope of the 3D simulation is from the exhaust pipe to the tail pipe.

To start with, Fig. 19 shows the measurement results. The exhaust noise tended to increase as the pipes in the mufflers approached a coaxial configuration, and that the tendency is clearly shown in the high-frequency range, the same result as the single-chamber muffler. Next, Fig. 20 shows calculation results for a 1D simulation and for a 1D-3D coupled simulation. This figure should be treated as a qualitative comparison because the calculation process for each simulation is different because of functional restrictions of the WAVE[®] software. In a 1D simulation, the calculation results are not affected by pipe position, as

with a single chamber muffler, so a 1D simulation cannot re-create the tendency of the measured results. On the other hand, in a 1D-3D coupled simulation, the exhaust noise shows the tendency that the closer each pipe is in a coaxial configuration, the higher the sound pressure level is. Therefore, a 1D-3D coupled simulation can re-create the tendency of the measured results.

Figure 21 shows a comparison of the calculated emission gas flows using 3D simulations. In the case of the Type 3 muffler, in which the pipe is not in a coaxial configuration, the jet flow from the exhaust pipe goes into

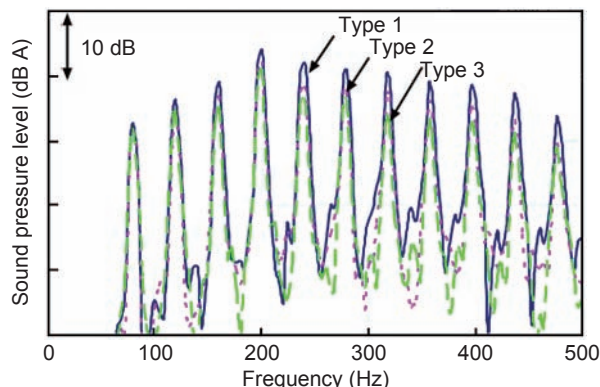


Fig. 19 Measured exhaust noise for different pipe positions

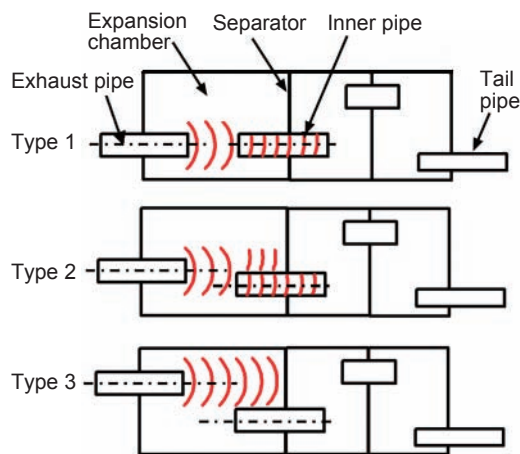


Fig. 17 Structure of multi-chamber mufflers

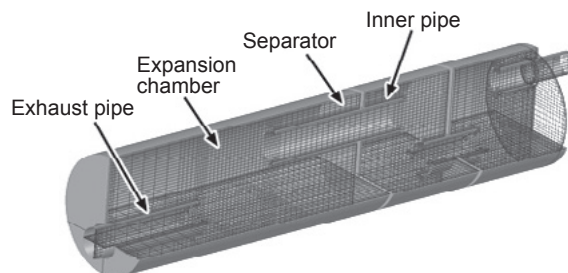


Fig. 18 3D-simulation model

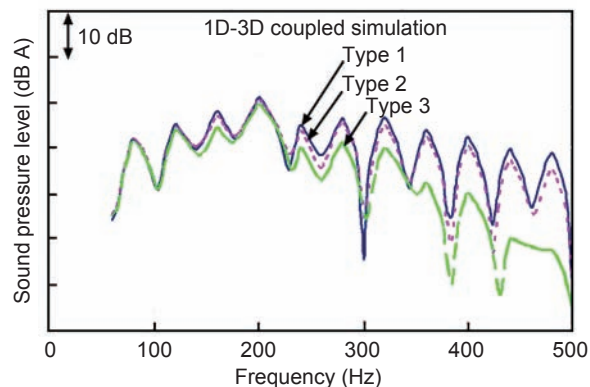
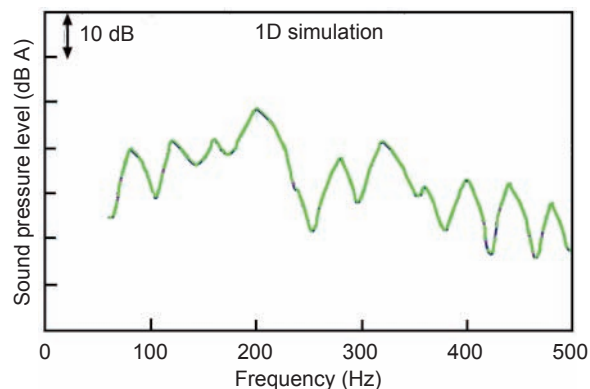


Fig. 20 Calculated exhaust noise for different pipe positions

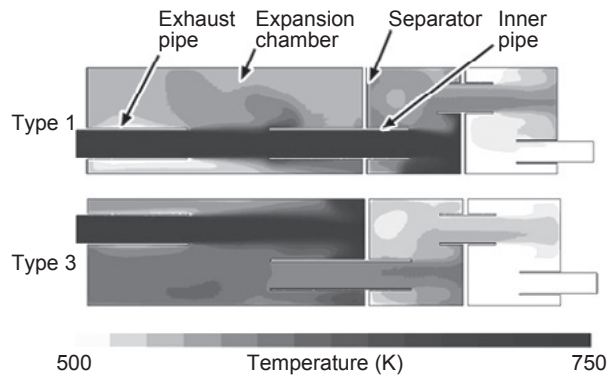


Fig. 21 Exhaust gas flow in muffler for different pipe positions (at ATDC 270 deg)

the inner pipe after running up against the separator. On the other hand, in the case of the Type 1 muffler, in which the pipe is in a coaxial configuration, the jet flow goes directly into the inner pipe without sufficiently expanding in the expansion chamber. For these results, it was found that there is a possibility to enhance the calculation accuracy of exhaust-noise by using a 1D-3D coupled simulation even in the case of muffler structure for which sufficient calculation accuracy cannot be obtained by using a 1D simulation.

4. Approach for Enhancement of Prediction Accuracy at the Initial Stages of Development

In the present accuracy verification, output power and intake-exhaust noise could be calculated with a higher accuracy by using the measured data of test motorcycles for part of the input conditions. However, at the initial stages of development, accurate calculations must be performed even when the measured data are not available as input conditions. So, a predicting method of input conditions to enable accurate calculations was developed.

- Intake-exhaust port flow coefficients: 3D computational fluid dynamics (CFD) calculations are performed for intake-exhaust port, and the obtained flow coefficients are used.
- Mechanical friction loss: Based on the friction loss of a similar engine, the value that calculates the amount of change from the dimensional difference of the part that becomes a friction factor and adds or subtracts it is used.
- Combustion conditions: In most cases, ignition timings for small-displacement single-cylinder motorcycles are set to the minimum advanced timing for best torque (MBT). Therefore, combustion conditions derived from ignition timings under full load in multiple mass production engines are used.

Figure 22 shows the results of calculated maximum output power and overall intake-exhaust noise for test motorcycles (A), (B), and (C) using the predicted input conditions. The maximum differences with the case that

the measurement value is used for the input conditions are about 0.3 kW in output power and about 0.5 dB in the intake-exhaust noise, therefore it can be said that there is sufficient accuracy for practical use. From these results, it was verified that output power and intake-exhaust noise can be calculated with a sufficient accuracy even when using the predicted input conditions.

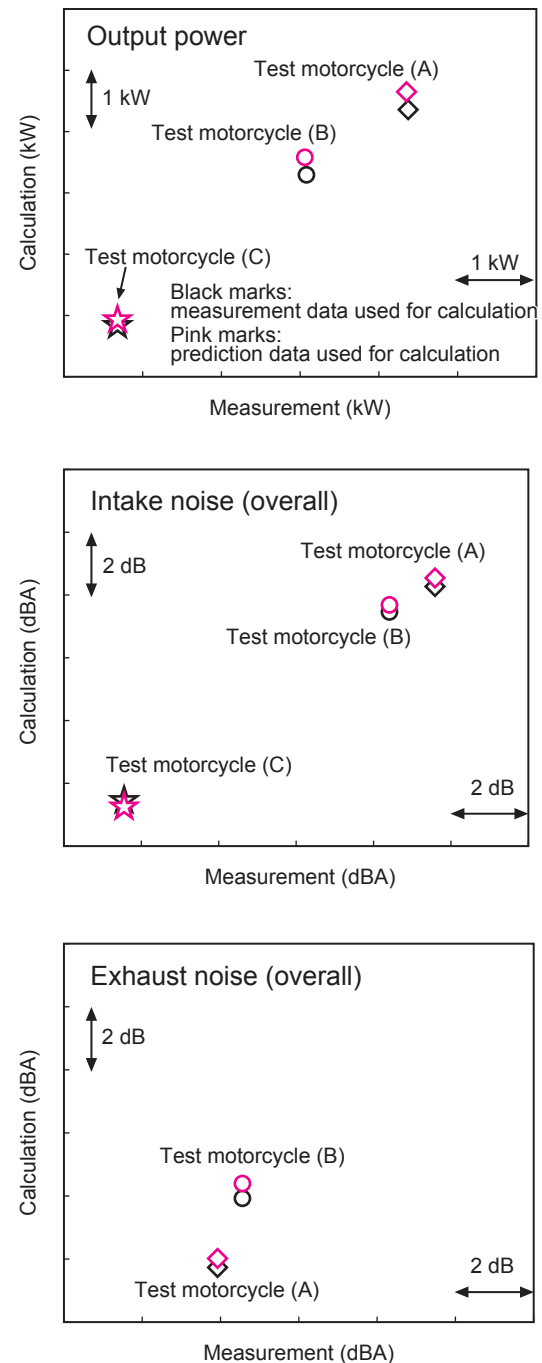


Fig. 22 Change in output power and intake-exhaust noise when using prediction data

5. Conclusion

A prediction technology that can concurrently calculate both the output power and intake-exhaust noise for small-displacement single cylinder motorcycles using a 1D simulation was constructed, and the following conclusions were obtained.

- (1) Output power can be calculated accurately.
- (2) Intake noise can be calculated accurately.
- (3) Exhaust noise can be calculated accurately provided that the pipes in the muffler are not in a coaxial configuration.
- (4) Sufficient calculation accuracy of the exhaust noise is not obtained by using a 1D simulation when the pipes in the muffler are in a coaxial configuration, and there is a possibility to enhance the calculation accuracy by using a 1D-3D coupled simulation.
- (5) Output power and intake-exhaust noise can be calculated with sufficient accuracy by using the predicted input conditions even when the measured data are not available as an input condition.

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