

# Clarification of Mechanism of Exhaust Orifice Noise via Exhaust Pulsating Flow Simulation

Masato SAKURAI\*

Kenichi TANAKA\*\*

Yuuya KASAJIMA\*\*

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## ABSTRACT

Regulations relating to environmental noise generated by automobiles are becoming increasingly stringent, making it essential to develop simulation technologies to contribute to the reduction of exhaust noise. The authors attempted to make the pulsing exhaust flow produced by an internal combustion engine visible using Schlieren photography and to visualize the source of exhaust orifice noise using noise holography. The knowledge obtained from these experiments was used to develop an exhaust pulsating flow simulation technology for exhaust orifice noise that enables quantitative prediction of levels. The major components of exhaust orifice noise are compression waves and ring vortices; the new simulation technology enabled further clarification of the mechanism of production of this noise.

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## 1. Introduction

Exhaust noise is classified into two types, radiation noise and orifice noise. The mechanism of radiation noise already revealed that pressure fluctuation in the pulsing exhaust flow excites the exhaust system structures to be a source of radiation noise<sup>(1)</sup>. This research presents an analysis of the mechanisms for generating orifice noise. Although orifice noise largely affects environmental noise, currently, R&D has lagged behind in understanding the generation mechanisms and in simulation technology. In order to clarify the generation mechanisms of orifice noise, it is necessary to gain a better understanding of the phenomena arising at the end of the exhaust pipe. The authors carried out a Schlieren visualization of exhaust orifice flow and attempted another visualization of the orifice noise source using acoustic holography. After understanding the phenomena, Computational Fluid Dynamics satisfying the conditions for analyzing vortex rings in detail was selected, and numerical analysis was performed to find the orifice flow noise source. Calculating the sound power of the sources of orifice flow

noise also pointed the way to a practical and precise procedure for finding propagation into the sound field. This paper reports that the visualization experiments and exhaust pulsating flow simulation technology were used in an attempt to clarify the mechanisms involved in generating exhaust orifice noise.

## 2. Generation Mechanisms of Orifice Noise

First, the mechanisms by which exhaust pulsating flow is propagated into the surrounding field as noise is considered. Part of the internal energy due to the pressure and velocity of the exhaust pulsing flow appears as structural excitation forces that apply to the exhaust pipe and the silencer, and from there, propagates to the surrounding field as noise.

The authors' conclusions from their previous experiments and calculations led them to the assumption that orifice noise originates from the noise source at the orifice end, and propagates away as an acoustic wave (Fig. 1).

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\* Tochigi R&D Center

\*\*Tokyo Denki University

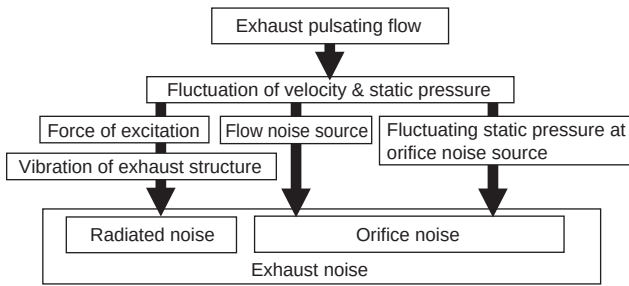


Fig. 1 Mechanism of generation of exhaust noise

Two main sources of orifice noise have been identified, the noise source at the orifice of the exhaust pipe, and that of the flow noise. A flow visualization experiment was therefore conducted in order to confirm the above assumption and gain a better understanding of the phenomena. Next, a Computational Fluid Dynamics (CFD) simulation was performed to find the orifice noise source; the sound power of the exhaust orifice flow was also calculated to compare the predicted noise level in the sound field quantitatively with measured sound pressure level.

### 3. Technology for Experimental Analysis

The exhaust pulsating flow in the exhaust pipe arrives at the orifice and is ejected as orifice flow. Schlieren photography was used to visualize the flow, in order to view the noise sources for the orifice noise. Then, non-steady acoustic holography, which can be used with time history data, was employed to visualize a wide area around the source of the exhaust orifice noise.

#### 3.1. Experimental Method for Schlieren Photography Visualization

The beam from a xenon source was reflected from a concave mirror to create a parallel beam which passed through the region to be measured (target), collected by another concave mirror and focused onto a knife-edge. The portions of the target from which the beam was diffracted toward the knife-edge were darkened, and the portions from which the beam was diffracted away from the knife-edge were brightened. This method enabled visualization by contrasting brightness in the density distribution of the target. The photographs were taken by synchronizing the light source triggering

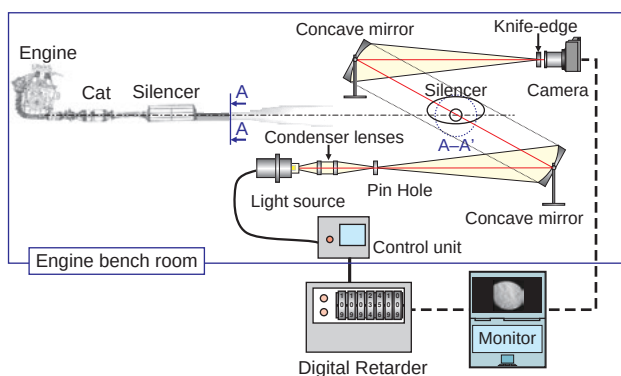


Fig. 2 Schematic of experimental apparatus

with the engine speed and setting the trigger delay time with a digital retarding circuit to obtain frames of the desired conditions. Figure 2 shows a schematic view of the experimental apparatus.

#### 3.2. Results of Schlieren Photography Experiment

Figure 3 shows Schlieren photographs of the exhaust orifice flow obtained at 3000 rpm when firing (with combustion) and motoring (without combustion).

The following items were observed in this visualization:

- (1) A large number of vortices were confirmed in the exhaust orifice flow. The density of vortices was found to be higher at higher exhaust temperatures (Firing mode). The density of vortices was lower during motoring mode.
- (2) A large occurrence of vortex rings was confirmed. These were clearly visible under the lower density fluctuations in the orifice flow during motoring (blue lines in Fig. 3). They were less clearly defined during firing, due to a large number of vortices.
- (3) No shock waves<sup>(2)</sup> were observed in the exhaust pipe near the orifice.

#### 3.3. Method for Non-steady Acoustic Holography Visualization Experiment

The acoustic intensity was measured at intervals of  $240 \mu\text{s}$  with a microphone array ( $6 \times 11$ ) whose center was placed 100 mm from the end face of the silencer (Fig. 4).

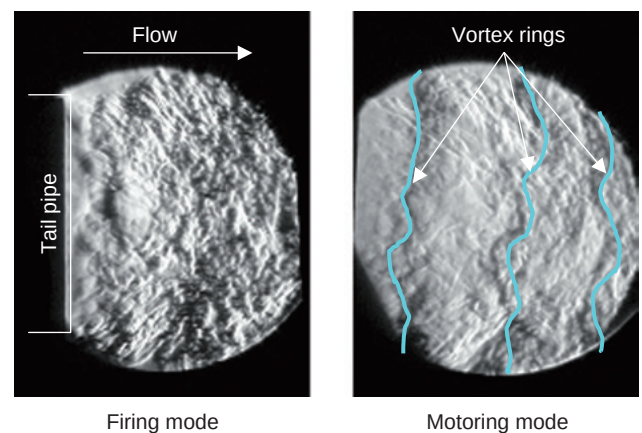


Fig. 3 Schlieren photograph of exhaust orifice flow (3 000 rpm, Th15%)

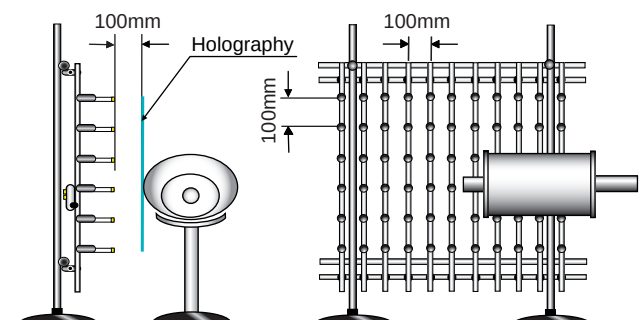


Fig. 4 Schematic of nonsteady acoustical holography

### 3.4. Non-steady Acoustic Holography Experimental Results

The non-steady acoustic holography visualization of the orifice noise source indicated the following two phenomena:

- (1) Each source of noise released from the orifice propagates at sonic speed and diffuses in a spherical pattern.
- (2) The centers of some orifice noise sources were observed to migrate away from the orifice (white spots in Fig. 5).

This migration matches exactly with the flow speed during the pulsations of the orifice flow. It was assumed that the sources migrate due to the flow.

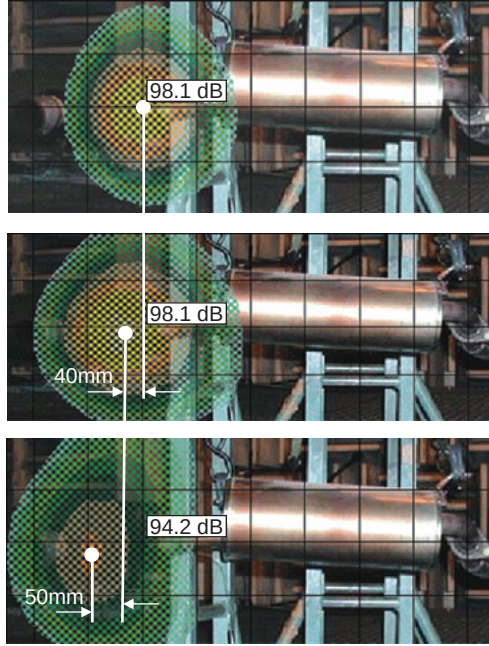


Fig. 5 Nonsteady acoustical holography of exhaust orifice noise (5 000 rpm WOT:Wide Open Throttle)

## 4. Simulation Technology

In real internal combustion engines, the exhaust pulsation is produced by the exhaust process, after cylinder combustion process. Inconsistencies in the combustion and other factors affect the exhaust orifice noise. In this research, a physical model of a high-speed exhaust pulsation generator that does not have combustion inconsistencies or other such factors was employed in order to compare and verify the simulated orifice noises.

### 4.1. Verification Experiment Apparatus

A comparison test was conducted using computational numerical analyses and actual results obtained in a high-speed exhaust pulsation generator<sup>(3)</sup> which modeled an internal combustion engine, without any actual combustion process. This flow generator used the rotary valve diagrammed in Fig. 6. Rotation of the internal element induced a pulsating flow in the right portion of the test pipe. The pulsation flows propagated down the pipe to the outlet, where they entered an anechoic room. The orifice flow was visualized with Schlieren photography. The test pipe was 1 m long. Semiconductor pressure sensors were installed in the pipe 100 mm downstream from the valve (Point A) and 100 mm upstream from

the orifice (Point B) to observe changes in the static pressure due to pressure waves traveling through the pipe<sup>(3)</sup>. The absolute pressure in the plenum tank (left side of the pipe) was 1.5 times that of the ambient atmospheric pressure (Pressure ratio = 1.5). The pressure of the orifice noise was measured at the sound field with a microphone 1 m from the right exit of the pipe and at a 45° angle off the pipe centerline.

### 4.2. Computational Numerical Analysis

The testing revealed that all of the following conditions for numerical methods need to be satisfied simultaneously, in order to conduct a successful computational numerical analysis of the exhaust pulsating flow in the pipe and of the orifice flow:

- (1) Compressible fluid analysis for the exhaust pipe inner flow including compression-expansion waves and shock waves
- (2) Non-steady analysis of fine structures (turbulence, vortex rings, etc.) in flow fields
- (3) Aeroacoustic analysis for flow field and sound field pressure fluctuations

In this research, a commercially available CFD solver<sup>(4)</sup>, satisfying the above conditions by applying the governing Navier-Stokes equation, the law of mass conservation, and the law of energy conservation was used for conditions (1) and (2). For condition (3), the sound power level was practically calculated to predict the acoustic pressure level, accounting for attenuation with distance, at the observation point.

### 4.3. Compressible Flow Numerical Model

The numerical model was the 2-dimensional axially symmetric model shown as Model A in Fig. 7. The node pitch was 0.25 mm. The initial inner pressure of the high-pressure tank was set at 150 kPa. The exhaust pulsations were generated at the valve, which was described using an Arbitrary Lagrangian-Eulerian (ALE)<sup>(5)</sup> mesh (Fig. 8). It is necessary to solve for shock waves and other compressible fluid phenomena in the exhaust pipe, as mentioned above in 3.1, so the simulation model with compressible fluid analysis was used, assuming conditions of an isentropic heat exchange between the inside and outside of the pipe.

### 4.4. LES Calculation Model

In order to solve the fine flow structure at the orifice, a Large Eddy Simulation (LES)<sup>(6)</sup> was used as the model for turbulence in a pseudo-compressible approach (Model B, Fig. 7). The calculation results at 100 mm upstream from the orifice in Model A (Point B) were used as the boundary conditions for the entrance to Model B

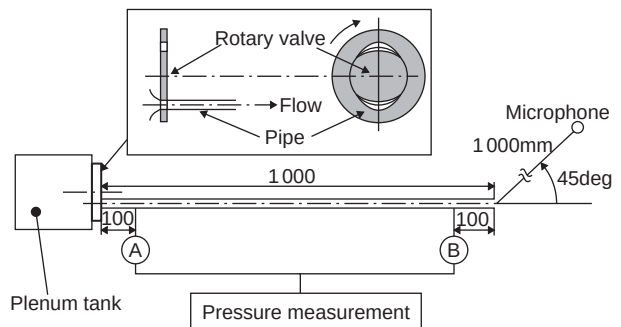


Fig. 6 Schematic of experimental apparatus

(Point C). The boundary of the orifice flow model was made Silent boundary.

A quad-shell mesh with equal pitch of 0.25 mm was used in both Models A and B. The total number of elements in both was about 500 000.

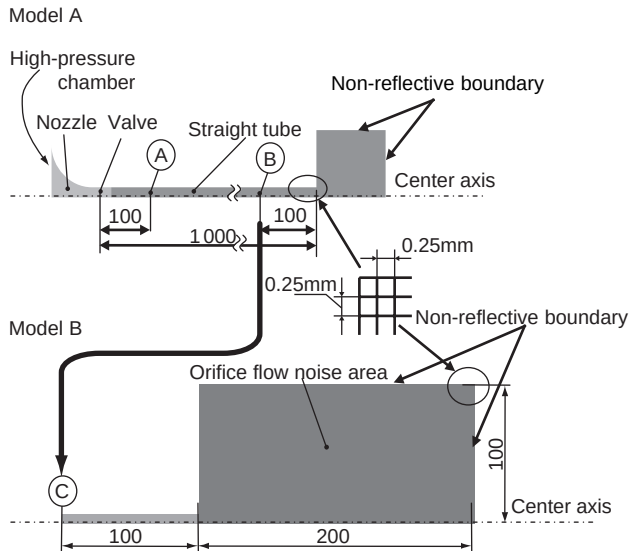


Fig. 7 Calculation model

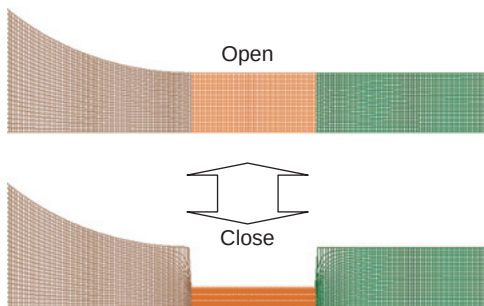


Fig. 8 Valve ALE model

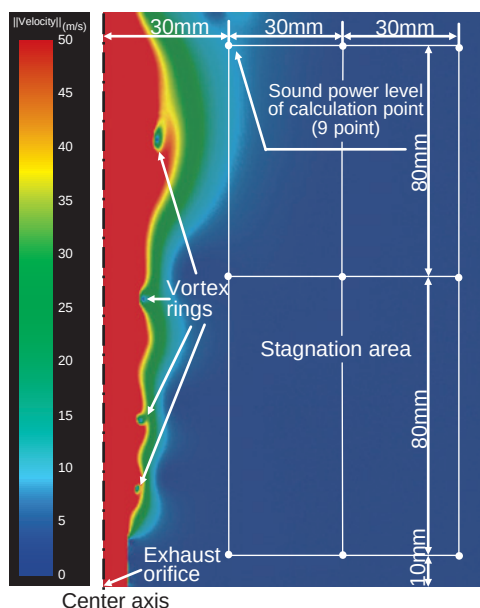


Fig. 9 Calculation model of sound power level

#### 4.5. Sound Power Calculation Model

The near sound field, affected by the orifice flow, comprises pseudo-sound waves<sup>(7)</sup>. “Pseudo-acoustic waves” mean the field of pressure fluctuations near the flow field which is affected by orifice flow. An acoustic numerical method employing the acoustic source based on Lighthill’s analogy can be used to find acoustic pressure levels in a sound field which is unaffected by pseudo-acoustic waves<sup>(8),(9)</sup>. In this research, however, the sound power of the orifice flow was calculated, and the sound pressure level remaining at the observation point, after attenuation with distance, was estimated. This method requires the model for calculating sound power to be in a stagnation region unaffected by the flow field. Nine locations in the stagnation area of the flow unaffected by the orifice flow were selected for measuring sound power (Fig. 9), using the results of the numerical fluid model.

#### 4.6. Results of Numerical Calculations for Pulsating Pipe Flow

Figure 10 shows the numerical results for the pressure distribution in the pipe. Figures 11 and 12 show the time history of the pressure in the pipe 100 mm downstream from the valve (Point A) and 100 mm upstream from the orifice (Point B), respectively.

The numerical results reproduced the compression and rarefaction wave distribution in the pipe. Notably, the compression wave region included a complicated distribution, due to the combined influences of reflected waves from both the orifice and the valve (Fig. 10).

Figures 11 and 12 indicate a generally good match between the experimentally observed results and the calculated results. The compression portion of the waveform was steep at the pipe end, verifying the process of growth toward a shock wave.

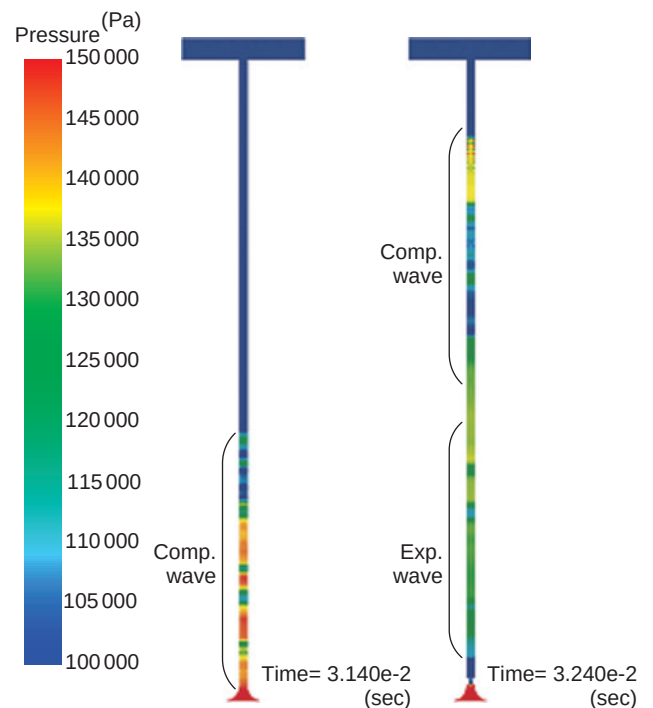


Fig. 10 Pressure distribution (contour map)

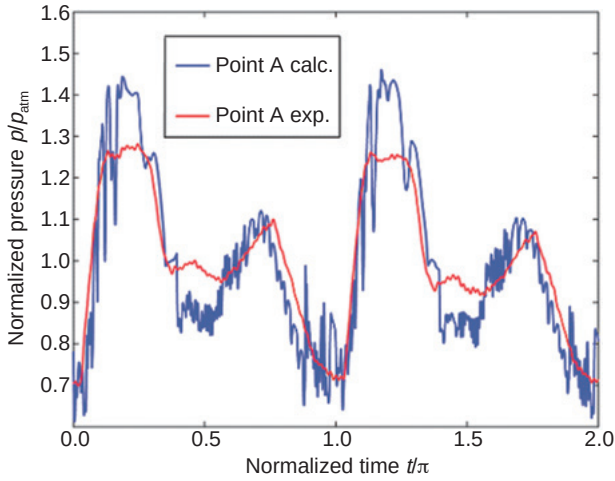


Fig. 11 Pressure history at Point A

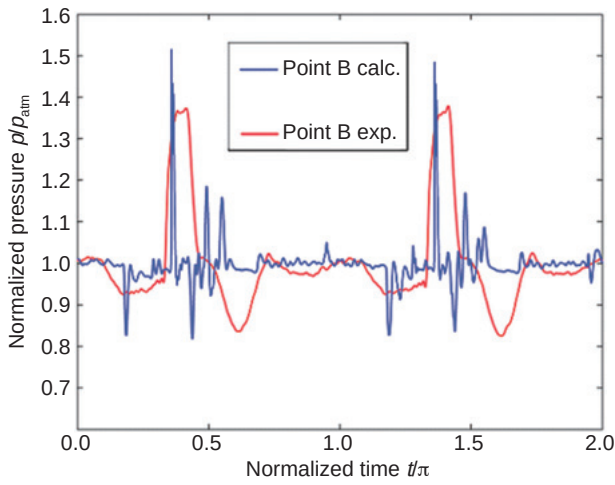


Fig. 12 Pressure history at Point B

#### 4.7. Results of Numerical Calculations for Flow near Pipe Orifice and Orifice Flow

Figure 13 shows the calculated results in the vicinity of the orifice. Compression waves arriving at the orifice are shown to spread out in a spherical pattern centered on the outlet, developing into orifice flow including multiple vortex rings. This phenomenon was also observed in the visualization by Schlieren photography (Fig. 14).

It is common to use multiple-stage expansion structures in silencers to attenuate compression waves<sup>(10)</sup>.

Figure 15 presents the calculated orifice flow in the exhaust space. There is a procession of pressure fluctuation distributions centering on the vortex rings. The fluctuations in pressure increase as the vortex rings develop. This indicates that vortex rings are one of the main orifice noise sources<sup>(11)</sup>.

#### 4.8. Results of Numerical Calculations for Orifice Noise

The mean acoustic pressures in the frequency spectrum was found using multiple CFD nodes that comprised the measurement planes in the axially symmetric sound power model. The sound power levels were calculated and, in turn, the orifice noise in the sound field was obtained.

The general relationship between the acoustic energy density  $E$  [w·sec/m<sup>3</sup>] and acoustic source output  $W$  [w] is given by Eq. (1):

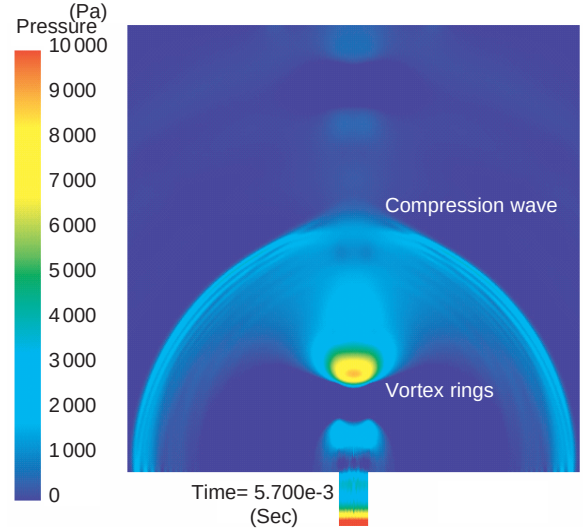


Fig. 13 Pressure distribution at exhaust orifice

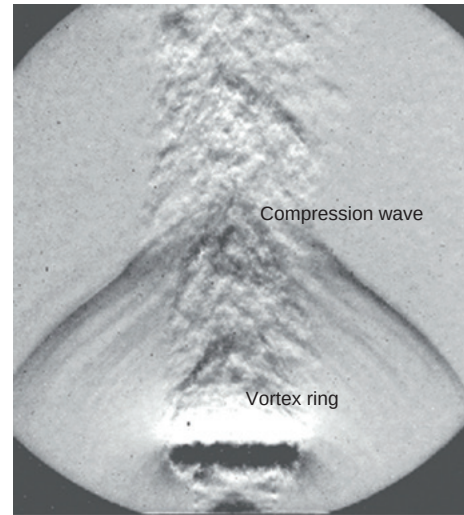


Fig. 14 Schlieren photograph at pressure ratio 4.0

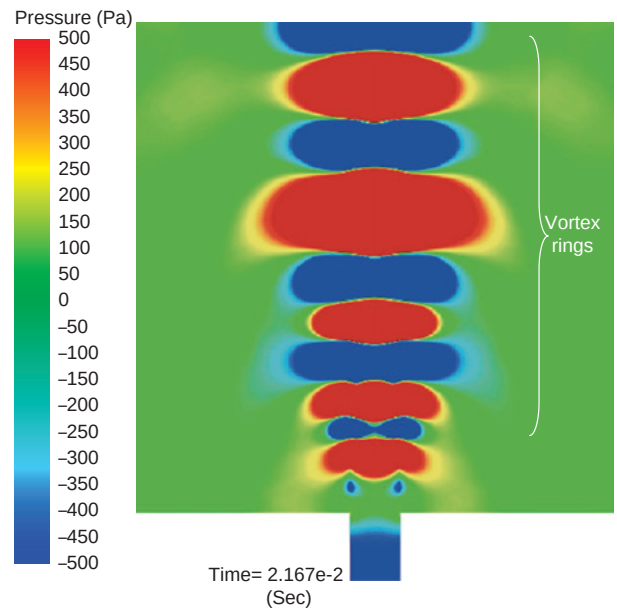


Fig. 15 Pressure distribution of vortex rings

$$E = \frac{W}{4\pi r^2 c} \quad (1)$$

$r$ : Distance from acoustic source [m]

$c$ : Sound speed [m/sec]

When the acoustic pressure at the observation point is  $L_{mic}$  [dB], the sound power level is  $L_w$  [dB] and  $10E-12$  [w] = 0 dB, the following relation is found:

$$L_{mic} = L_w - 11 - 20\log_{10}r \quad (2)$$

The relationship between sound power level  $L_w$  and the mean pressure at the observation point for sound power  $L_p$  [dB] was

$$L_w = L_p + 10\log_{10}(S) \quad (3)$$

$S$ : Area over which sound power is measured [m<sup>2</sup>]

This provided the orifice noise pressure level  $L_{mic}$  [dB] at the observation point.

Figure 16 shows a comparison of the calculated frequency spectrum and measured orifice sound pressure levels at the sound field 1 m from the orifice. The peak error was generally within 10 dB up to about 4 000 Hz, a comparatively good match. Above 4 000 Hz, the measured acoustic pressure levels tended to exceed the calculations. This is because of the short sound power levels in the vicinity of vortex rings at high frequencies used for these calculations. It is likely that the settings for the sound power observation point affects the precision of measurements of the air flow noise.

#### 4.9. Mechanisms of Orifice Noise Generation according to Numerical Analysis Results

The numerical analysis clarified the following mechanisms of orifice noise generation:

- (1) The pressure distribution of compression-expansion waves was seen in the pipe and the compression waves showed a sharp pressure rise with distance along the exhaust pipe. Upon reaching the orifice, the pressure spread in a spherical pattern centered on the compressible wave arriving at the orifice. These phenomena were confirmed using high-speed exhaust pulsation generator and orifice flow visualization experiments.

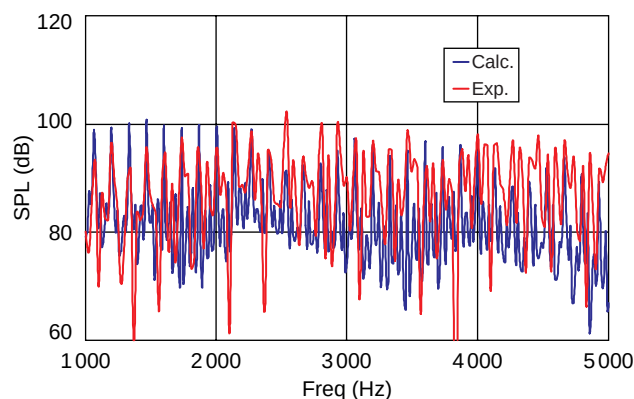


Fig. 16 Comparison of orifice noise at microphone (1 m)

- (2) Vortex rings were formed in the orifice flow region and a pressure distribution was observed to spread in the vicinity of this region with movement of the vortex rings. These phenomena, including the vortex rings, were confirmed using Schlieren photography to visualize the orifice flow.
- (3) The acoustic pressure spectrum of the sound field (1 m from the orifice), calculated using the sound power level in the orifice flow field, exhibits the pulsating noise that contains sharp peaks due to its multiplicity of compressive waves synchronized with the exhaust flow. The spectrum also has a broadband pressure distribution in the high-frequency spectrum, the main component of air flow noise, yielded by calculating the sound power of noise sources near the vortex rings. The calculated spectrum was confirmed to show nearly the same trends as those of the spectrum of the noise measured at the observation point.

## 5. Conclusion

On the basis of experimental and computational numerical analysis, exhaust orifice noise, which is the main component of exhaust noise, has been shown to occur due to the following mechanisms:

- (1) The main factors in the generation of exhaust orifice noise are pressure fluctuations occurring when compression waves and orifice flows in the exhaust pipe are ejected from the orifice. Orifice noise sources have been broadly classified into two types, propagation of acoustic waves due to compression waves centering on the orifice, and pressure fluctuations centering on vortex rings in the orifice flow.
- (2) Pressure fluctuations due to compression waves propagate into the sound field in a spherical pattern and become pulsating noise. They are synchronized with exhaust flow pulsations.

Multiple vortex ring acoustic sources move with the orifice flow. They grow, diffuse and become air flow noise, having a broadband pressure distribution in the high-frequency spectrum.

A numerical solution procedure created in this paper is confirmed to be effective in simulating exhaust pulsating flow and in clarifying these phenomena. PC calculation resources now allow flow simulations, using flow calculations limited to 2-dimensional axially-symmetric flow, and sound power calculation. A practical tool for analyzing the mechanisms of phenomena in exhaust orifice noise has been created.

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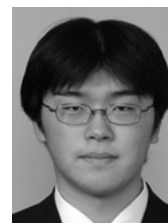
■ Authors ■



Masato SAKURAI



Kenichi TANAKA



Yuuya KASAJIMA