

Predictive Simulation of Flow-induced Noise using CFD

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ABSTRACT

A method of predictive simulation of flow-induced noise using computational fluid dynamics has been developed. In order to simulate flow-induced noise, it is necessary to compute detailed vortex flows and density change of air. This paper introduces the existence of flow-induced noise predicted by unsteady compressible flow calculations using large vortex simulation, a type of turbulence model. The target flow-induced noise for prediction was narrow-band noise, also known as whistling noise, a type of noise in which sound increases at specific frequencies. With the exhaust pipe, including the complex shape of the silencer, as the subject of predictive simulation of flow-induced noise, predictive accuracy was verified by simulating the measurement conditions of steady-state flow. The developed method makes it possible to judge whether narrow-band noise will be generated or not, and to identify the position of the sound source.

1. Introduction

Today, demand is increasing for the reduction of the burden placed on the environment by cars and trucks and for the realization of increased fuel efficiency. As part of this trend, in the area of powerplants the use of hybrid vehicles is becoming more widespread and vehicle chassis are being reduced in weight. At the same time, from the perspective of commercial appeal, it is desirable to reduce noise occurring in the vehicle cabin in order to increase passenger comfort. Carmakers are working to develop noise abatement technologies targeting the various sources of cabin noise, including engine noise, road noise, and flow-induced noise. Hybrid cars are that the vehicle interior of a room became calm, flow-induced noise becomes conspicuous as cabin noise. Flow-induced noise is produced when a flow of air strikes an object. In the case of a car, flow-induced noise occurs in a variety of areas where airflows exist, for example around the exterior fittings, in the air conditioner, and in the exhaust pipe.

Flow-induced noise can be divided into two types: broad-band noise and narrow-band noise (Fig. 1). In the case of broad-band noise, sound pressure increases across a broad frequency range, as shown in Fig. 1 (b). Wind roar corresponds to this type of noise. In the case of narrow-band noise, sound pressure increases only at specific frequencies,

as shown in Fig. 1 (a). Narrow-band noise produces a sound like whistling. Because of this, vehicle occupants are prone to become aware of narrow-band noise, and it represents an issue from the perspective of commercial appeal.

The development of a method of predictive simulation of flow-induced noise would be desirable from the perspectives of the achievement of increased efficiency in the development process and the realization of increased quality. Because flow-induced noise is sensitive to small changes in the shape of elements including small steps and crevices and the curvature of flow paths, prediction at the blueprint stage would be desirable. Conventionally, it has not been possible to conduct evaluations of whether noise that represents an issue will be generated until the measurements are made using prototypes. If it is judged based on measurements that correction is necessary, it is

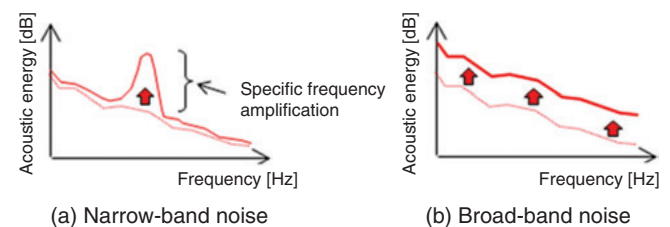


Fig. 1 Classification of flow noise

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then necessary to identify factors and modify the shape, and therefore change the design. Commercial computational fluid dynamics (CFD) software offers computation models⁽¹⁾ based on steady-state calculation as a method of simulating broad-band noise. However, because narrow-band noise necessitates fluid computations that take time history changes into consideration, resulting in a high computation load, the method is challenging to apply.

Sound is propagated by cyclical changes in the density of the air forming a wave motion. In order to simulate sound, it is essential to perform fluid computations of sufficient resolution to achieve an understanding of flow fields that include minute vortex flows that produce infinitesimal pressure fluctuations. In addition, by contrast with noise generated by the vibration of structures, high-frequency components are dominant in flow-induced noise, and the target frequency band is 1000 Hz and above. Because it is necessary to finely discretize computation space and time in order to compute high-frequency components with short wavelengths, the computation burden is further increased. However, recent advances in computer performance have made it possible to compute detailed vortex flows. Simulation methods using the computation methods Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) have been reported as methods of computing flow-induced noise^{(2), (3)}. With regard to efforts to reduce flow-induced noise, the application of measures to the areas around the door mirrors has been reported⁽⁴⁾, but few reports have thus far been produced.

The research discussed in this paper developed a technology for the prediction of flow-induced noise, with narrow-band noise as the specific target. Comparison of simulation and measurement results indicated that the method was a predictive method able to reproduce measured phenomena. Because the aim for the developed prediction method was application in the vehicle development process, the research sought to produce a method with an appropriate level of accuracy and an appropriate computation burden for application in development.

2. Target for Computation

2.1. Selection of Target for Computation

The target for computation for the development of a narrow-band noise simulation was a steady-state flow test in a silencer and exhaust pipe combination (the combination is simply termed “exhaust pipe” here). The internal structure of the exhaust pipe was made up of complex shapes, encompassing areas in which small holes are formed in the pipe and separators, thin pipe walls, curvature and branching of pipes, and connections between parts (Fig. 2). Because of this, there were numerous areas that represented factors in producing noise, and this made identifying the noise sources an issue. In order to reproduce the phenomenon of noise production, the actual shape rather than a simplified shape was used in measurements and simulations.

2.2. Narrow-band Noise

Figure 3 shows the method used to measure noise in the exhaust pipe. Figure 4 shows the measurement results. The results show that from 5000 rpm to 6000 rpm, sound pressure is higher close to 3800 Hz than in other frequency domains. This is narrow-band noise.

Exhaust noise is made up of a variety of types of noise, including noise produced by flows, noise produced by sudden temperature differentials, and noise produced by the vibration of structures. Flow-induced noise in the exhaust system is generated when the exhaust pulse from the engine changes as a result of engine speed, changing the flow in the exhaust pipe. It is thought that when narrow-band noise is being generated, cyclical fluctuations in volume are occurring due to typical structures in the interior of the exhaust pipe. Under certain flow-speed conditions, there is mutual interference between cyclically generated vortices, producing cyclical fluctuations in pressure, resulting in

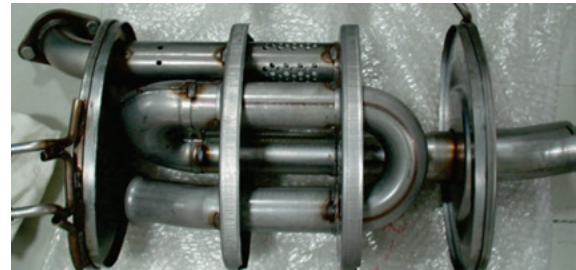


Fig. 2 Silencer internal structure



Fig. 3 Noise measurement landscape

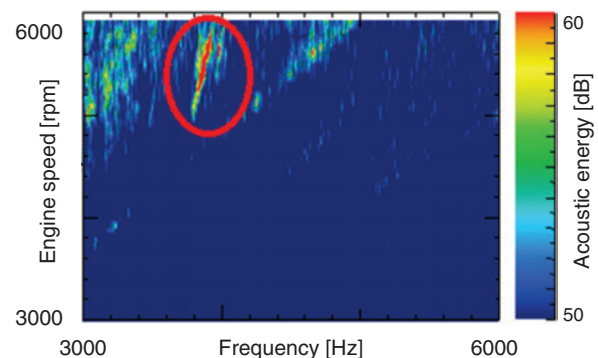


Fig. 4 Noise measurement result

the generation of noise due to phenomena such as the generation of edge tones or cavity tone at the various structures inside the exhaust pipe⁽⁵⁾.

2.3. Development Goals

The aim of prediction of narrow-band noise was to make it possible to study items at the blueprint stage that it was previously not possible to judge without measurement. The following three development goals were set for the predictive simulation:

- (1) Ability to judge, during the vehicle development process, whether an unacceptable level of narrow-band noise will be generated;
- (2) Prediction of the peak frequency of generated noise to an accuracy of ± 200 Hz; and
- (3) Ability to identify the position of the sound source.

3. Development of Analytic Methods

Narrow-band noise occurs because there is a mechanism in the exhaust pipe that amplifies sound in specific frequency domains. The computation of this amplification mechanism necessitates the use of a method that enables the unsteadiness of the flow field and the propagation of pressure to be understood at a high level of spatial resolution, rather than the conventional method, in which a time-averaged flow field is solved for use when determining the flow rate, pressure loss, and coefficient of resistance. The computation burden produced by the extremely high mesh number needed for the use of the method represented an issue, but large-scale parallel computation dispersed the burden, making it possible to obtain a solution within a practical time frame.

3.1. Application of Turbulence Model LES

In order to calculate flow, a model for carrying out the numerical computation of the turbulent flow is used. Reynolds-Averaged Navier-Stokes equations (RANS) and LES are the two representative turbulence models. Figure 5 shows a comparison of LES and RANS. RANS models and computes the entirety of turbulent motion, and is mainly suited to the solution of steady-state averaged flows. LES directly computes comparatively large vortices using the Navier-Stokes equation, and models and computes fine flows. LES is able to simulate more detailed flows than

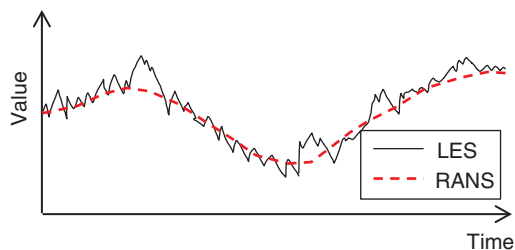


Fig. 5 Comparison of LES and RANS

RANS, and is also superior in simulating highly unsteady phenomena such as vortex shedding.

3.2. Consideration of Compressibility

In order to simulate the minute changes in pressure occurring as a result of the formation and dispersion of turbulent vortices, in calculating the density of the air, it is necessary to calculate pressure-dependence using the equation of state of an ideal gas. Figure 6 shows the results of a simulation of cavity tone, a noise-producing phenomenon that occurs due to the curvature or the rapid expansion and contraction of a flow channel. The impact of the vortex formed at the edge upstream in the cavity against the edge downstream in the cavity produces a sound wave. The propagated sound wave promotes the generation of a still stronger vortex at the upstream edge. The repetition of this phenomenon in a fixed cycle produces a cavity tone. The use of computations that take compressibility into consideration makes it possible to express the propagation of sound waves and resonance within the cavity, therefore making it possible to simulate the existence of sound pressure peaks in specific frequency domains.

3.3. Application of Non-iterative Time Advancement

In order to understand the periodicity of flow fields by computation, it is necessary to conduct unsteady-state calculations for fixed time intervals. This increases computation costs in comparison to analyses in which time-averaged flow fields are determined. When the Non-Iterative Time Advancement (NITA)⁽³⁾ algorithm is applied, the outer iteration for each time step is performed only once. This makes it possible to reduce computation cost in comparison to the conventional complete Iterative Time Advancement (ITA) algorithm (Fig. 7). Figure 8 shows that the overall trends reproduced by ITA and NITA correspond, but that the detailed pressure fluctuations are not reproduced in the NITA simulation. Because of this, it was necessary

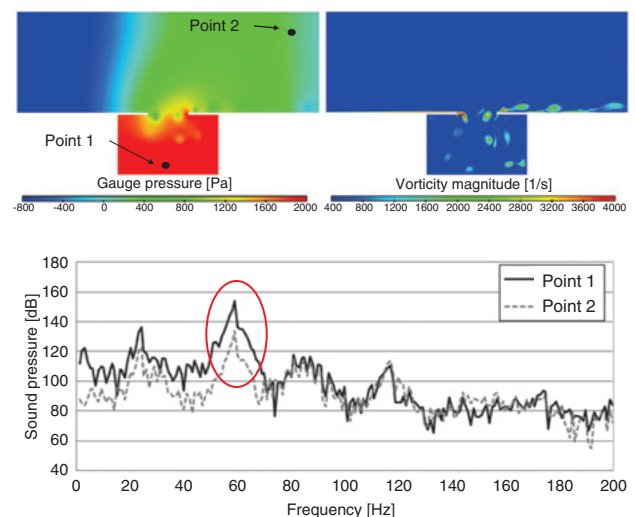


Fig. 6 Cavity tone calculation results

to use NITA only during the process until a convergence solution was obtained, switching to conventional ITA when periodicity was observed in the pressure fluctuations.

3.4. Setting Conditions

In addition to a high level of spatial resolution, a high level of time resolution is necessary in order to understand the flow motion that produces narrow-band noise. As will be discussed below, because the subject of the analysis in the present research was the several-kHz frequency domain, flow motion with a periodicity of the 0.1 ms-order could be considered to occur. To compute this flow motion, it would be necessary to divide this cycle into several tens of 0.001 ms-order time-step lengths. In addition, in order to obtain computational stability using computational fluid dynamics, it is necessary to set mesh size to produce Courant numbers of the 1 to 10^1 orders. Time-step length and mesh size were determined on this basis. The flow rate ratio during flow test measurements was set as the inlet boundary condition. Atmospheric discharge was set as the outflow boundary condition. The temperature of the fluid was ambient temperature.

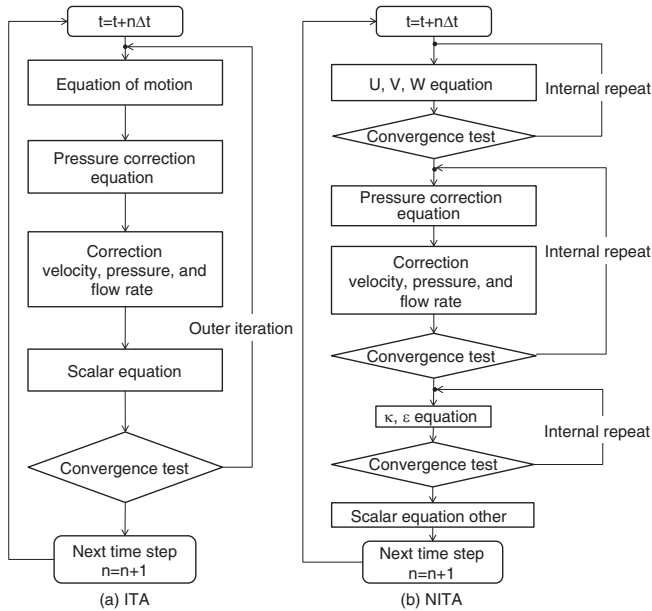


Fig. 7 Convergence process

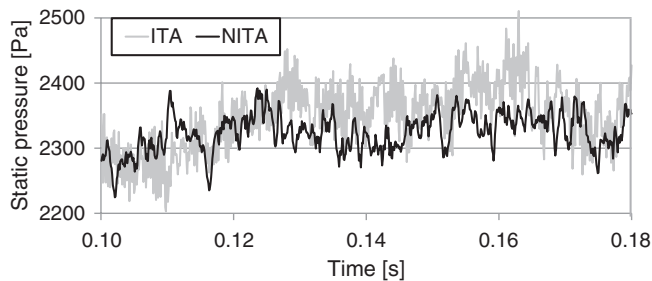


Fig. 8 Pressure fluctuation comparison

In order to reduce computation time, the solution of a steady-state fluid analysis was set as the initial flow field. Unsteady-state computation was commenced, and a pressure monitoring point positioned in the analytic domain was monitored. When the simulation results were stable and periodicity was observed in the pressure fluctuations, data for evaluation was sampled.

3.5. Form of Analysis

Figure 9 shows the shape of the entire exhaust pipe used in this research. Flow visualization measurements were able to verify that sound-absorbing materials in the chambers inside the exhaust pipe would have minimal effect on the downstream section of the pipe. The shape of the chambers upstream of the branch was excluded from the fluid analysis. Figure 10 shows an interior view of the silencer. Inside the silencer, there are numerous small holes, in a pipe and in the separators. Tests conducted prior to this study indicated that the effect of vortices generated close to these holes would have a strong effect in producing noise, and the holes in their entirety were therefore modeled using mesh for this computation.

Excluding sound propagation from consideration made it possible to restrict the computation space to the shape of the interior of the exhaust pipe. In sound simulations, it is usual to make both the formation of the sound source and the propagation of sound to the measurement position subjects of computation. It was possible to compute the formation of the sound source by means of unsteady compressible flow calculation using LES, as discussed above. Sound propagation can be computed by fluid

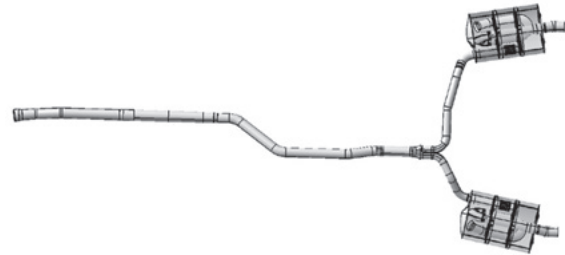


Fig. 9 Entire exhaust pipe

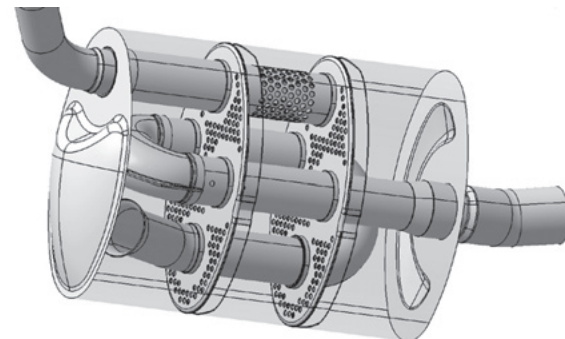


Fig. 10 Inner view of silencer

computation or acoustic computation. Because sound attenuation does not have an effect when propagation is not considered, the absolute value of sound pressure cannot be compared. However, it is considered possible to judge whether or not narrow-band noise will be generated from the surrounding sound and the difference between the outstanding peaks. To compute propagation using fluid computation, it is necessary to take reflection and other factors into consideration and utilize a large computation space of several meters. The solution of propagation necessitates the use of mesh that divides the wavelength of the sound wave into between 15 and 20 subdivisions. Assuming that the subject of a simulation was a maximum frequency of 5000 Hz, the wavelength would be 68 mm, and the minimum necessary mesh size would be no more than 4.5 mm. The discretization of a space of several meters using mesh of 4.5 mm or less would dramatically increase the mesh number, thus also increasing the computation burden. For this reason, in the present study narrow-band noise was determined without consideration of propagation in order to reduce the computation burden.

3.6. Computation Space

The flow field computed by LES is dependent on the resolution of the mesh. Prediction of whether or not narrow-band noise will be generated necessitates a mesh size that makes it possible to understand the behavior of the turbulent vortices that induce it. Figure 11 shows the results of LES computation of the formation of Karman vortex streets following the passage of a uniform flow through a cylinder. Because the simulation possessed sufficient spatial resolution with regard to the diameter of the cylinder and the velocity of the flow, it was possible to compute the

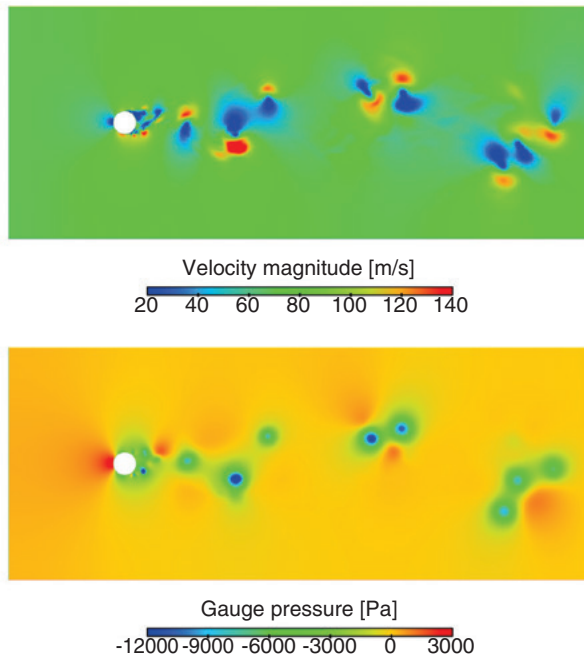


Fig. 11 Cylinder flow calculation results

formation of alternate vortex streets, and to verify that areas of low pressure are generated cyclically. As a result of the fact that the necessary spatial resolution is dependent on the flow velocity and characteristic length of the flow field (in this case, the diameter of the cylinder), it is necessary to select the appropriate spatial resolution for each subject of analysis.

3.7. Application of Cartesian Grid Cut-cell Method

In order to accurately compute the flow inside the exhaust pipe, it is essential to express the holes in the pipe and separators and the thickness of the pipes in mesh shapes. For shapes of this type, the cut-cell method not only offers ease of mesh generation and mesh size control, but also presents advantages in terms of the reproducibility of shapes at boundaries (Fig. 12).

Because local mesh size control made it possible to refine mesh size exclusively in areas in which the flow is complex, computation time could be reduced by reducing the mesh number. Hexagonal mesh formed using Cartesian grids makes it possible to use higher-order space finite differences rather than tetrahedral mesh of equivalent size. This helps to enable control of numerical diffusion, and is effective in making possible accurate computation of local pressure fluctuations.

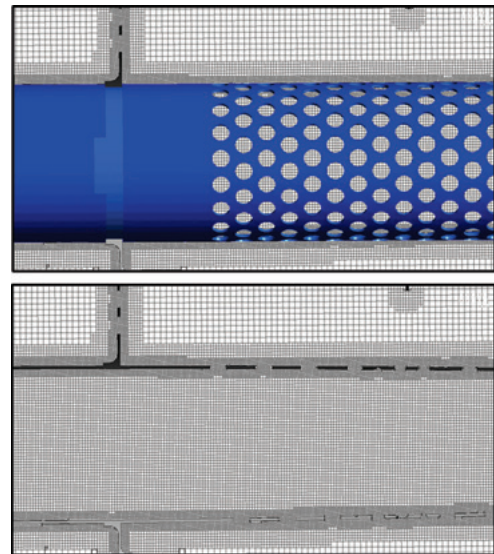


Fig. 12 Cut-cell mesh

4. Study

4.1. Evaluation Method

4.1.1. Comparison with measurements

Measurement data for sound pressure around the outlet of the exhaust pipe for inlet conditions producing narrow-band noise was compared with measurement data for pressure inside the pipe. Figures 13 and 14 show the results of frequency analyses of each set of measurement

data. While figures differ because both sets of data were separately measured, they both display peaks at close to 2800 Hz. This indicates that there is a strong correlation between sound pressure at the exhaust pipe outlet and pressure fluctuations inside the pipe. With this as a precondition, in the present simulation observation points were situated inside the exhaust pipe, and the existence of narrow-band noise was predicted with pressure fluctuation as a criterion for judgment. Situating the observation points inside the exhaust pipe restricted the computation space for the simulation to the interior of the pipe. This made it possible to reduce the computation load.

4.1.2. Evaluation of sound

Figure 15 shows the observation points used in the simulation. Because it was not possible to output sound data for each observation point from fluid calculations, time history data for static pressure was used. Fast Fourier Transform (FFT) was applied to the static pressure data to convert it into frequency components, and sound was evaluated. The data-sampling period was set as 0.15 s, and

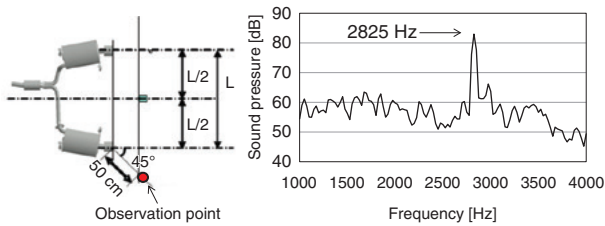


Fig. 13 Sound pressure measurement

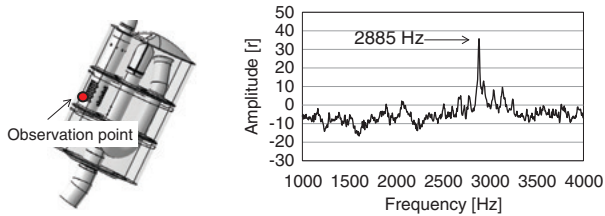


Fig. 14 Pressure measurement

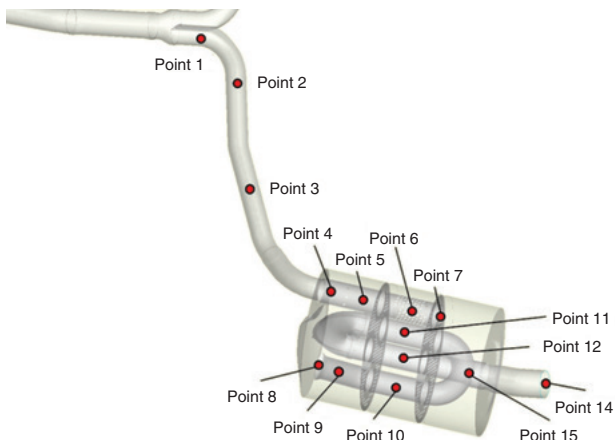


Fig. 15 Simulation observation points

Table 1 Implementation condition

Shape	Pressure [Pa]	Measuring peak frequency [Hz]
A	4000	2600
A	5500	2825
B	5500	No Peak

data was output at 1×10^{-4} s intervals. Sets of 0.15-s data were subdivided into 0.04-s units, and FFT was applied with an overlap of 50%. Frequency resolution was 25 Hz.

4.1.3. Method of judgment of occurrence of narrow-band noise

Judgment during the development process of whether or not unacceptable narrow-band noise would occur was based on the degree of prominence of the peak frequencies. The level of background noise other than the target noise was estimated from the results of frequency analysis at each observation point, and its difference with peak values was calculated. The existence of narrow-band noise was judged by comparison of these differential values with values determined by measurement.

4.2. Implementation Conditions

An overview of the measurements that represented the implementation conditions for the simulation is shown in Table 1. Table 1 shows the shape, the back pressure conditions, and the frequency of narrow-band noise occurring at the time of measurement. The subjects of comparison in this case were differences in back pressure and differences in shape. A comparison was conducted for Shape A in Fig.16 at back pressures of 4000 and 5500

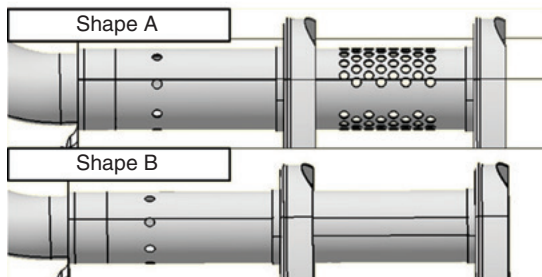
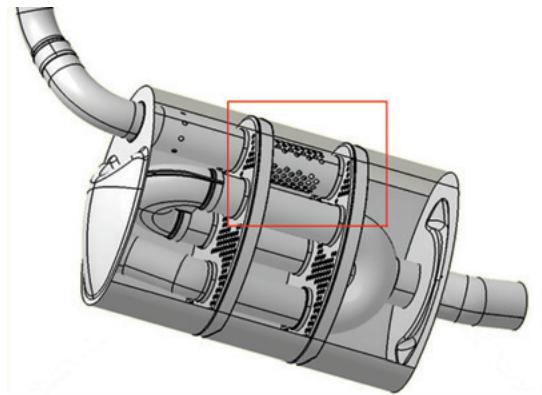


Fig. 16 Shape difference specification

Pa. The measurements show that the peak frequencies for narrow-band noise shifted in response to back pressure conditions. In terms of shape difference, Shape A and Shape B, in which the holes in the pipe were filled in (Fig. 16), were compared. For Shape B, no narrow-band noise was generated, and no frequency peaks were observed. Simulation results for the two conditions discussed above were compared, and the accuracy of the simulation was verified.

4.3. Results of Analysis

This section will discuss the results of comparison of the simulation and measurements. The values from the simulation were computation results for pressure at each observation point within the exhaust pipe. This discussion will focus on Point 7 in Fig. 15.

4.3.1. Results for different back pressure conditions

Figure 17 shows the results of a comparison of the simulation and measurements. Because the observation points differed between the measurements and the simulation, absolute values for sound pressure do not correspond, but the results match in terms of the general tendency of existence of peaks. In both simulation and measurement results, clear peaks occur at approximately the same frequencies. The frequency shift and increase in sound pressure when the back pressure condition is increased from 4000 to 5500 Pa was also reproduced by the simulation. In addition, because criterion values were exceeded under back pressure conditions of both 4000 and 5500 Pa, it was assumed that narrow-band noise was generated. Given the above, it can be concluded that narrow-band noise can be predicted by simulation.

4.3.2. Results for different shapes

Figure 18 shows a comparison of measurement and simulation results for Shape B, in which the holes in the pipe inside the silencer had been filled in, under a back pressure condition of 5500 Pa. Across the entire frequency range, no conspicuous peaks exist in either the measurement or simulation results. In addition, the peaks occurring at a back pressure of 5500 Pa for Shape A in Fig. 17 are

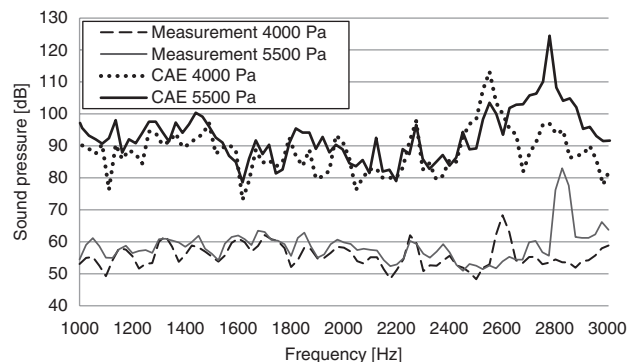


Fig. 17 Comparison results of pressure conditions

Table 2 Peak frequency comparison

Pressure [Pa]	Measurement [Hz]	CFD [Hz]	Difference [Hz]
4000	2600	2550	50
5500	2825	2775	50

significantly reduced in the case of Shape B. With regard to the occurrence of narrow-band noise, the difference between the peak close to 2800 Hz and background noise was minimal, and it was therefore judged that narrow-band noise was not generated. CAE and measurement results for the non-occurrence of narrow-band noise under differing shape conditions also corresponded. Based on the above, it can be concluded that it is possible to predict the non-occurrence of narrow-band noise by simulation.

4.3.3. Verification of accuracy

Because target values for the determination of CAE accuracy in the present research were evaluated in the 1/3rd-octave band when measurements were evaluated, the deviation between frequencies in the measurement and CAE results was set at ± 200 Hz, falling within this range.

Table 2 shows the deviation between frequencies occurring in measurement and CAE results for Shape A. The deviation is 50 Hz for a back pressure condition of 4000 Pa and 50 Hz for 5500 Pa. Target values were realized under both back pressure conditions, indicating that the developed method displays sufficient accuracy for prediction.

4.4. Identification of Sound Source

The ability to predict narrow-band noise also makes it possible to identify sound sources from calculation results. Sound sources were identified by means of comparison of power spectrum density (PSD) values at each observation point.

Figure 19 plots PSD values at 2775 Hz for each observation point. This graph shows the magnitude of sound at 2775 Hz at each observation point. The maximum PSD value at Point 7 can be considered to be the sound source. Figure 20 shows contour diagrams of differences in static pressure over time in a cross-section

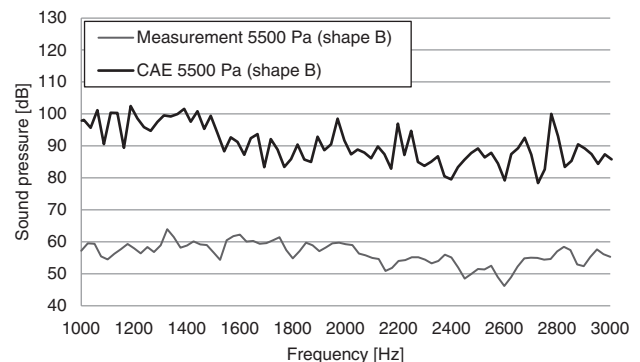


Fig. 18 Results with different shapes

of the silencer. Figure 20 (a) and (b) show results for different computation times. The circled areas are believed to be the sound sources. It is clear that changes in static pressure over time in the circled areas are greater than in other areas. The phenomena shown in Figure 20 (a) and (b) are repeated cyclically. This indicates that it is also possible to predict that noise will be generated from a contour diagram based on cyclical fluctuations in static pressure in one position.

The results of sound source identification measurements showed that the same position was the sound source for each shape. The fact that the sound source was located in the same position despite the

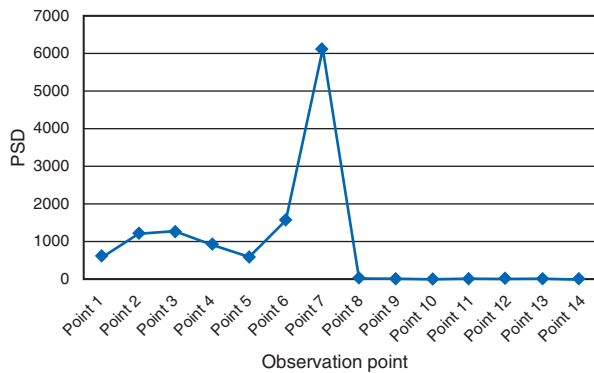


Fig. 19 2775 Hz-PSD

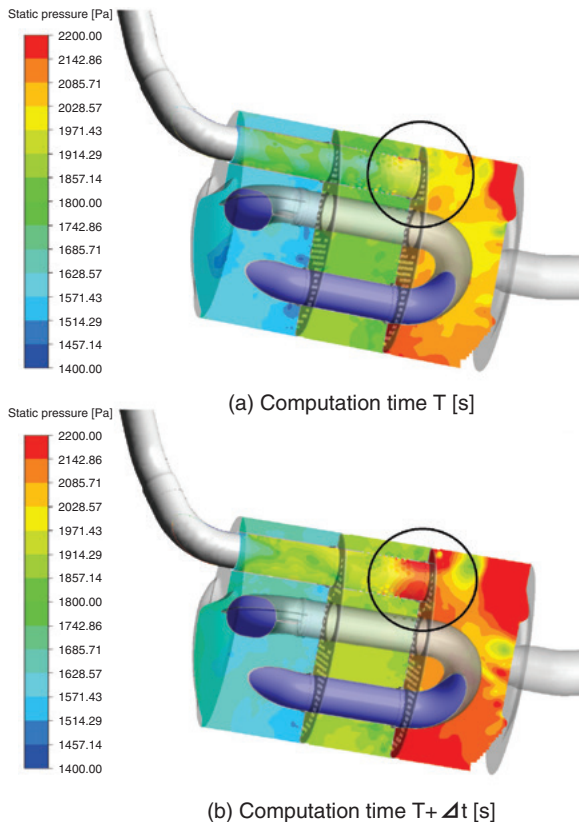


Fig. 20 Static pressure of silencer section

differences in Shape A and B indicates that correction of the shape of the sound source would have an effect on the existence of narrow-band noise. The results discussed above verified that sound sources could be identified from CAE results.

5. Conclusion

A method of predictive simulation of narrow-band flow-induced noise using CFD has been developed. Because the target for prediction in this method was narrow-band noise, fluctuations in fluid pressure in the analytic domain were focused on. The three goals set for the development of the simulation method were realized as follows.

- (1) Simulations of the generation of narrow-band noise from pressure fluctuations were conducted based on fluid computation using LES. Criterion values were set, making it possible to predict the existence of noise that would represent an issue.
- (2) For the subject of the analysis, predictive accuracy for peak frequencies was a deviation of 50 Hz. It was verified that the target accuracy of within ± 200 Hz was realized.
- (3) It was verified that the position of the sound source could be identified by comparing the magnitude of peak frequencies at each observation point based on fluid computation results.

The developed method has made it possible to judge whether narrow-band noise will occur and to identify the position of the sound source prior to the manufacture of prototypes using three-dimensional shape data. It is thus possible to predict the existence of noise and correct the relevant shapes at an early stage of the development process. In the future, in order to quantitatively evaluate the generated sound pressure, it will be necessary to separate sound pressure fluctuations from fluid pressure fluctuation calculations, and conduct simulations that consider the propagation path from the sound source to the reception position outside the exhaust pipe.

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