Aerodynamic Noise Simulation Technology for Developing Low Noise Products

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ABSTRACT

The size reduction trend of electric power equipment causes increased heat generation density along with an accompanying need for increased airflow for cooling. In this situation, aerodynamic noise can be the dominant noise source for air-cooled electric equipment. Grasping the noise generation mechanism and the noise reduction by measurements are often difficult, getting physical information through simulation can be an effective approach. In order to achieve noise reduction of equipment, we elucidated the aerodynamic noise generating mechanism by focusing the fan, the main source of noise in air cooling equipment, and estimated noise change caused by cooling structure differences. Simulated sound pressure level and peak frequencies are in good agreement with the measurement. This technology can be applied to understand the noise generation mechanism, and can also be used to structure design.

1. Introduction

The trend toward smaller electric equipment products is causing them to have a higher heat generation density. To help this heat dissipate, a common measure taken for air cooling systems is to increase the airflow. However, the aerodynamic noise generated from the cooling air may become an issue as the air volume increases. Aerodynamic noise is caused by pressure variations generated due to flow disturbance. In order to clarify and take measures for this phenomenon, techniques that mainly use measurements have been traditionally applied. However, taking measurements is often difficult if the object to be measured rotates or moves or the space to be measured is large, for example. To address this issue, it is effective to run a simulation that allows a large quantity of physical information to be obtained in the target space. Note, however, that an aerodynamic noise simulation requires that turbulence phenomena are accurately reproduced and tremendous amounts of computation time are necessary.

In response, in addition to improving computer processing speeds, parallel computing using more than one CPU has been applied for reducing the computation time. Taking floating point operation per second (flops) as an example, the "Earth Simulator" achieved 35 trillion operations (35 Tflops) in 2002 and the "K computer" 10 quadrillion operations (10 Pflops) in 2011. This means that a computational speed increase of 100 times was achieved in about 10 years. Following this development, faster computers for science and technology purposes owned by private companies and an improved and diffused cloud environment available for public use have made it possible to perform massively parallel computing. In addition, execution speeds of computations performed for research and development have been improving dramatically.

This paper describes aerodynamic noise simulation technology intended for power electronics equipment with an air cooling structure.

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2. Products and Noise

2.1 Types of noise and related products

Figure 1 shows major types of noise sources and related products of Fuji Electric. Noise sources can be roughly classified into mechanical vibrations, electromagnetic vibrations and aerodynamic pressure variations. Noise caused by mechanical vibrations is mainly generated in products with mechanical structures that involve rotation and/or movement such as rotating machines. Noise resulting from electromagnetic vibrations is mainly generated in products in which electromagnetic force works, such as transformers. Noise caused by aerodynamic pressure variations is mainly generated in products such as air-cooled devices and power electronics equipment. Many products have their heat-generating components cooled by using fans and establishment of the technology is expected to produce a ripple effect among products.

2.2 Issues with analysis of aerodynamic noise

In order to reduce the noise resulting from flow, any unsteady turbulence phenomenon that provides an acoustic source should be identified so that appropriate measures can be taken. Flow analysis here allows the user to capture a wider range of flow phenomena as compared with measurement and is becoming an effective tool.

The Reynolds-averaged Navier-Stokes (RANS) model is generally used for flow analysis of turbulence

UPS

PCS for photovoltaic power generation

Motor

Data center

Fuel cell

Vending machine

Field	Related product	Major noise source		
		Mechanical vibration	Electromagnetic vibration	Pressure variation of fluid
Power electronics equipment	UPS, PCS, power supply, inverter, etc.	–	Core (reactor)	Cooling fan
	Motor	Resonance, bearing	Core/coil	Cooling fan, rotor
Industry	Clean room, data center	–	–	Fan filter unit
	Electric distribution facility	–	Core (reactor)	Cooling fan
Power generation/society	Turbine/peripheral equipment	Resonance, bearing	–	Labyrinth seal
	Generator	Resonance, bearing	Core/coil	Cooling fan, rotor
	Fuel cell	–	–	Cooling fan
Power reception and distribution/control equipment	Magnetic contactor	Contact collision	–	–
Food distribution	Vending machine	Compressor vibration	–	Cooling unit fan

Fig.1 Types of noise sources and related products

phenomena. It is based on the flow statistically time-averaged for specific flow conditions and cannot be said to adequately reproduce the phenomenon as a fluid analysis method. Meanwhile, large eddy simulation (LES) can be used to directly solve the behavior of eddies that cause a time variation of flow. However, LES requires more than 100 times as much computation time as RANS, and hence one issue was to reduce the computation time. Still, massively parallel computing that uses a few hundred to a few thousand CPUs, in addition to the improved computation time of recent CPUs, has led to a stage where LES computation is practicable[(1) to (4)].

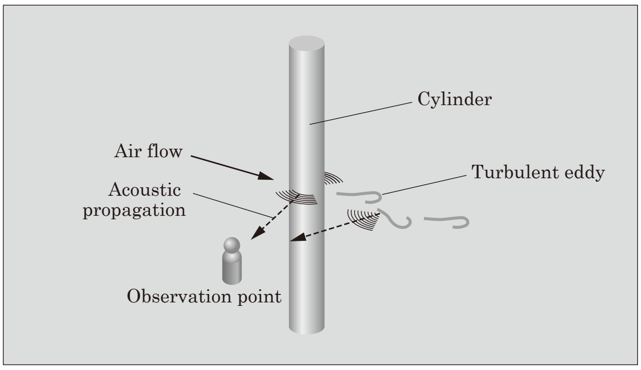

Fig.2 Mechanism of generation of aerodynamic noise with cylinder taken as example

3. Application of Aerodynamic Noise Analysis Technology

3.1 Principle of generation of aerodynamic noise

A mechanism of generation of aerodynamic noise that takes a cylinder as an example is shown in Fig. 2. Aerodynamic noise can propagate to an observation point from 2 types of acoustic source. One is an acoustic source caused by pressure variations on a solid surface generated by eddies and the other is generated by variations of momentum due to turbulent eddies (Kármán vortices) in a space. The level of noise of the former is proportional to the 6th power and of the latter to the 8th power of the flow speed. In a low-Mach-number region with a low flow speed, the former is dominant[(5)]. The flow speed from an air cooing fan considered in this paper is a low-Mach-number flow of about 20 to 30 m/s and the noise arising from pressure variations on a solid surface is dominant.

3.2 Analysis methods

Aerodynamic noise analysis methods can be roughly classified into direct noise simulation method and integral methods on acoustic analogy. Major characteristics of the 2 types of methods are listed in Table 1. There are differences in the computation time and type of information that can be obtained and the method should be selected according to the purpose.

The direct method determines the flow and acoustic propagation at the same time. By considering fluid compressibility, which is variation of the fluid density according to the pressure, the acoustic pressure variation can be analyzed at the same time. With this method, meshes for analyzing the wavelength of sound to the observation point are required in addition to

Table 1 Major characteristics of aerodynamic noise analysis methods

Item	Direct method	Integral method
Calculation method	○ Compressible flow + unsteady ○ Direct calculation of sound pressure	○ Incompressible flow + unsteady ○ Acoustic calculation from wall surface pressure
Fluid analysis	Unsteady compressible flow LES analysis	Unsteady incompressible flow LES turbulence analysis
Noise analysis		FW-H, Curle's equations*, etc.
Advantage of method	○ Precise method featuring high accuracy ○ Interference between object and sound field also reproducible	○ Allows relatively easy handling. Highly accurate as well ○ Computation time nearly adequate to be practical (a few days with existing machines)
Issue	Requires high spatial resolution and leads to ultra-large-scale computation	Coupling with sound field analysis necessary for considering reflection and sound absorption

*FW-H, Curle's equations: representative calculation methods for noise estimation with the distance from pressure variations on a solid surface to the observation point taken into consideration

meshes for reproducing turbulent eddies in a flow field in the vicinity of the acoustic source. For this reason, the direct method tend to require a larger number of meshes, and hence a longer computation time.

With the integral method, flow and sound are computed independently. After obtaining pressure variations on a solid wall surface by flow analysis, the sound at the observation point is estimated[(5) to (7)]. It is not necessary to consider compressibility of the fluid and it is sufficient to simply focus on meshes capable of reproducing the turbulent eddies that provide the acoustic source. This makes it possible to reduce the computation time as compared with the direct method.

In flow analysis, it is important to reproduce turbulent eddies that change over time. Currently, using LES for this reproduction is the most effective method. For the present target of verification, it is not practical to perform a few hundred to a few thousand parallel computations using the in-house computer facilities for completing LES computation in a few days. Accordingly, we have used the "K computer" for the computation. We have studied noise from the cooling fan unit and noise from the cooling fan and an obstacle in the case of using a cooling structure.

With the cooling fan unit, the pressure variations of the fluid that work on the blades and casing surface may provide an acoustic source to directly reach the observation point. For this reason, we used the integral method, which is relatively easy to handle. Meanwhile, in a structure with a cooling fan and obstacle, noises from the cooling fan and the obstacle and their interference are a possibility. Therefore, we used the direct method for studying the noise.

3.3 Analysis results

As shown in Fig. 3, we studied the noise generated in 2 types of configuration: a cooling fan unit and a cooling fan integrated into a cooling unit.

Using a wind tunnel conforming to the JIS B 8330, we measured the noise from the fan unit and obtained the fan characteristics (flow rate and pressure difference as well as flow rate and noise) at the same time. We used a model structure similar to the actual equipment, structure of which has flow resistance, i.e. a block installed in the flow channel that simulates electronic components and a heat sink.

(1) Fan unit

We used the integral method and performed calculation with the same layout and conditions as those used for measuring the noise. Figure 4 shows the flow speed distribution by LES at the maximum efficiency point. It has allowed us to reproduce the details of vortex variations in the fan wake flow, which was not possible with analysis by the conventional RANS.

The results of analysis and experiment on a sound pressure spectrum at the observation point are shown in Fig. 5. The horizontal axis represents the frequency and the vertical axis the sound pressure level. It indicates that the spectra observed consist of peak sounds and wideband sounds. With the blade rotation frequency represented by N, the peak sounds consist of 4N resulting from the casing shape, 5N or the blade

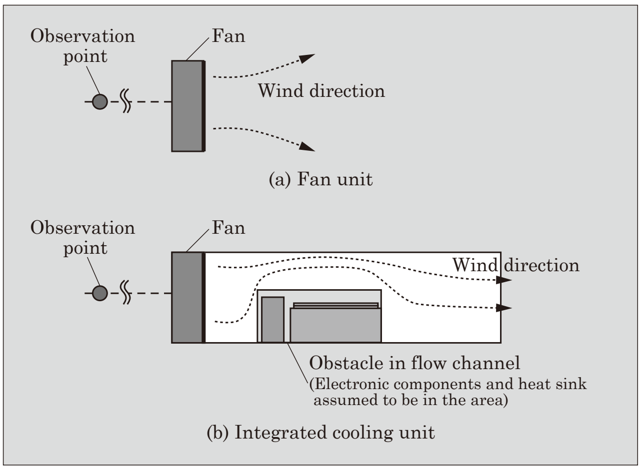

Fig.3 Structure studied

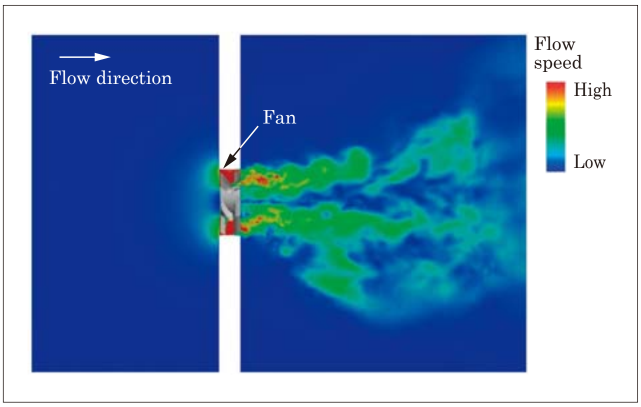

Fig.4 Flow speed distribution by LES at maximum efficiency point (instantaneous value)

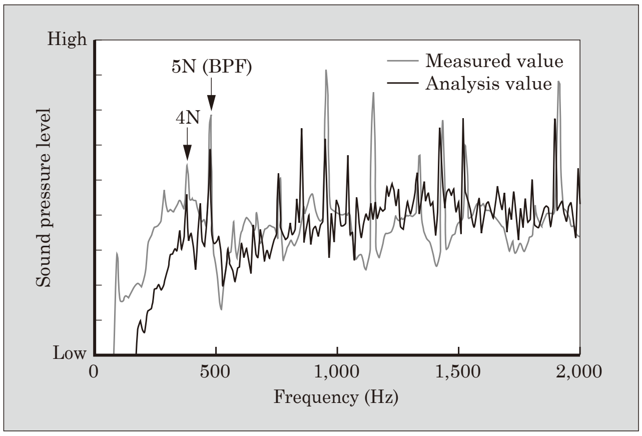

Fig.5 Sound pressure spectra for fan unit

passing frequency (BPF) resulting from the number of blades (5 blades) and their harmonic components. The portions that are not the peak sounds result from turbulence and are referred to as wideband sounds. In the analysis, of the peak frequencies, the peak sounds of 4N and BPF and wideband sounds, which provide the fundamental wave, are reproduced. In addition, the difference of the overall value (overall value of the sound pressure arrived at by adding up the sound pressure levels of the respective frequencies) between the results of analysis and measurement was not more than 5 dB. The reason why the measured values are at higher levels in the low-frequency region (approximately 300 Hz or lower) is assumed to be the acoustic effect of the measurement wind tunnel. Further, reproduction is estimated to become more accurate by including the wind tunnel structure in the target of analysis.

(2) Integrated cooling unit

We assumed a case of using actual power electronics equipment and studied the noise. The obstacle in the flow channel was modeled as a block to analyze the noise by using the direct method.

With the direct method, non-stationary variation of the sound level can be solved at the same time as the flow. Figure 6 shows the pressure distribution determined by LES at the maximum efficiency. It shows that the pressure propagates to the space upwind from the fan, i.e. the acoustic source. Because of the pressure change in the direction of rotation due to the blades, the pressure isosurface has a 3D structure. At this time, pressure variations at the observation point translate to sound. Figure 7 shows sound pressure spectra obtained in analysis and actual measurement. The analysis is generally successful in reproducing characteristics including the BPF and other peak frequencies, wideband noise distributed over wideband frequencies due to turbulence and resonance noise with peaks over a few hundred Hz. The results show that the analysis values are partly over-evaluated under 200 Hz. One factor in this is assumed to be that the effect of sound attenuation on wall surfaces of the

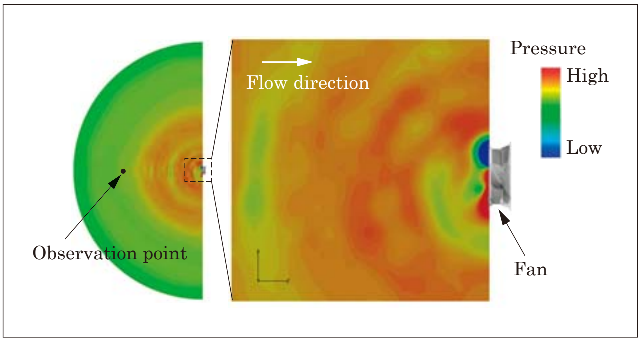

Fig.6 Pressure distribution at maximum efficiency point (instantaneous value)

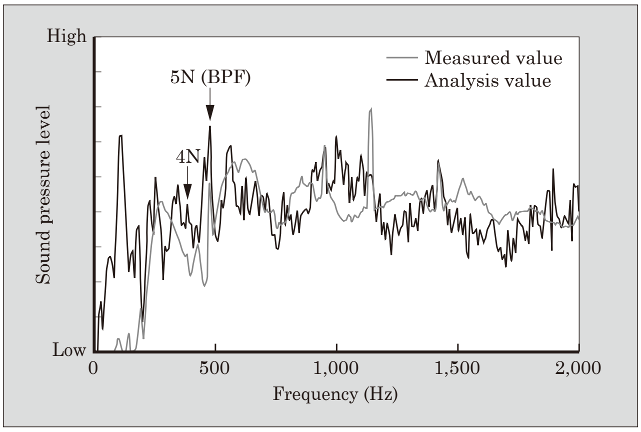

Fig.7 Sound pressure spectra with integrated cooling unit

structure is not taken into account.

When studying the cooling structure of a product, the distance between the fan and the obstacle as shown in Fig. 3(b) is one of the important design factors that should be considered for noise reduction. Accordingly, we used this method to verify the variation of the sound pressure level as this distance was varied (see Fig. 8). It shows that, as the distance increases, the sound pressure level decreases. This is considered to be a result of a decrease in the pressure variation generated by the flow from the fan outlet hit-

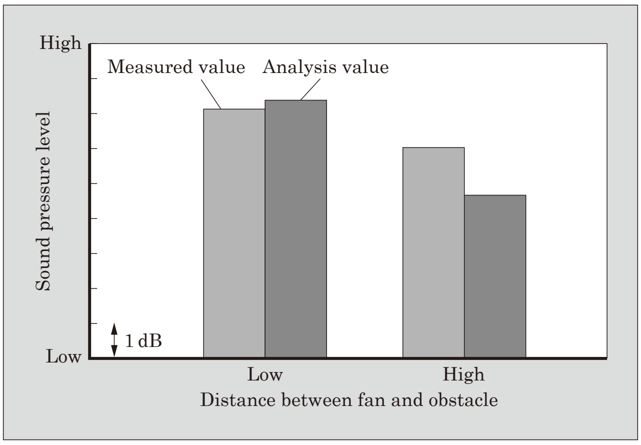

Fig.8 Distance between fan and obstacle and sound pressure level

ting the obstacle.

(3) Application of analysis results

We have obtained knowledge by studying noise with the fan unit and the cooling unit. And based on it, we are gradually working to apply aerodynamic noise analysis to the structural design of power conversion equipment such as uninterruptible power systems and power conditioning sub-systems.

4. Postscript

This paper has described aerodynamic noise simulation technology for developing low noise products.

Aerodynamic noise simulation has made it possible to visualize the variations of flow and pressure that provide noise sources. It can be used to grasp mechanisms and apply them to structural designs in order to reduce noise. In the future, we intend to contribute to eco-friendly product development while helping to enhance product performance, which are areas we have worked on up to now.

Some of the results mentioned in this paper have been obtained in cooperation with the organizations listed below. We would like to extend our sincere gratitude to the parties involved.

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WG3 is participated in by the following organizations: the University of Tokyo, Waseda University, Hitachi, Ltd., DMW Corporation, Ebara Corporation, Mizuho Information & Research Institute, Inc., Advanced Simulation Technology of Mechanics R&D, Co. Ltd.

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