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CONDITIONAL ANALYSIS OF VORTICES BETWEEN SIROCCOFAN BLADES BY POD OF SUCTION SURFACE PRESSURE

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ABSTRACT

To investigate the mechanism of sound generation from the blades of a Sirocco fan, LES of the separated and reattaching flow was performed using a stationary blade cascade model. Two types of blades with different blade thicknesses were used. POD analysis was performed to decompose the pressure fluctuations on the suction surface into various spatial modes. The force acting on the suction surface which is generated by the pressure fluctuations at each mode was calculated, and using it as a reference signal, conditional averaging of the pressure field was performed. It decomposed the pressure field of the whole domain into coherent vortices at various scales. This procedure is important to calculate the forces acting on the blades according to Curle's equation. The results suggest that the sounds generated by vortices at different scales may cancel each other. This cancellation may contribute to the noise-reduction of multi-blade fans such as sirocco fans.

INTRODUCTION

In recent years, the noise generated by car air-conditioners is getting relatively larger in the interior space of cars due to lower engine noise and reduced road noise, etc. There are several causes of noise from car air-conditioners, but the main one of them is aeroacoustic noise from the Sirocco fan. This noise is mainly caused by interference between the blades or casing and the vortices shed in the separated and reattaching flow. According to Curle (1955), with some assumptions, the noise from an object in the flow is proportional to the temporal derivative of the force acting on the object. Vortices interact with blades or casing surfaces and generate force acting on them, so analysing the vortices shed between blades is important to create a quiet fan.

In this study, POD (Proper Orthogonal Decomposition) analysis was performed to extract the coherent vortices between blades. POD is one of the methods to decompose a dataset into basis functions or modes based on optimizing the mean square value of the data. In the fluid dynamics community, POD is widely utilized to extract coherent structures from flow fields (Taira et al., 2017; Lumley, 1967). In this study, POD was performed to decompose the pressure fluctuations on the suction surface of the blade to extract coherent vortices that produce the pressure fluctuations or the noise from the sirocco fans.

METHOD

Numerical Settings

In this study, incompressible LES analysis was performed using OpenFOAM, an open-source numerical analysis software. The governing equations are the continuity equation and the Navier-Stokes equation with a spatial filter

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{u}_i\bar{u}_j + \tau_{ij}\right) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\nu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) \quad (2)$$

where $\bar{u}_i$ is the i-th component of the velocity, $\bar{p}$ is the pressure ($\bar{\ }$ denotes average by the spatial filter), ν is the kinematic viscosity that is set to 1.5 × 10^{-5} m^2/s, ρ is the density of the incoming fluid (air) that is set to 1.293 kg/m^3 and τ_{ij} is the SGS stress calculated using the dynamic Smagorinsky model. The time step in the simulations was 1.0 × 10^{-5} s. The computation time was set to 2.1 × 10^{-1} s.

Geometry and Boundary Conditions

In this study, two types of 2-D blade models with different blade thicknesses were used. One is the "original model" with a constant blade thickness from leading edge to trailing edge, and the other is the "filled model" in which only the shape of the suction surface is changed to fill the separation bubbles observed in the original model. Figure 1 shows the computational mesh of the blade models used in the simulations. In this study, the middle blade and the left

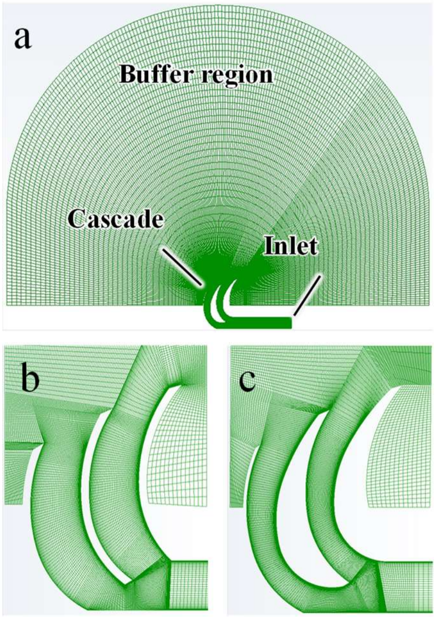

Figure 1. Computational mesh of (a) whole domain, vicinity of cascade of (b)original model and (c)filled model.

channel are focused on. In both models, the chord length is about 25 mm and the spanwise length is 20 mm. The number of meshes in each model is about 2.6 million. Preliminary calculations have been performed with several sizes of meshes to ensure that the results are qualitatively mesh-independent. A semicircular buffer region was set at the channel outlet to prevent the outflow boundary from influencing the flow field between the blades. The inlet flow velocity was 24 m/s and the pressure boundary condition at the inlet was set to zero-gradient. The channel and blades were treated as walls. At the outlet boundary, the velocity was set to zero-gradient, and the total pressure $\frac{1}{2}\rho\bar{u}_i\bar{u}_i + p$ was set to zero. The periodic condition was imposed in spanwise direction.

RESULTS AND DISCUSSION

Instantaneous Fields

Figure 2 shows the distribution of the instantaneous absolute value of the velocity $|\bar{\boldsymbol{u}}|$ for each model at time t = 2.1 × 10^{-1} s. The figure shows that the flow is separated from the blade surface in both models. The fluctuation of the separated shear layer indicates that the Kelvin-Helmholtz instability causes the vortex to roll up. In the original model, separation occurs at the leading edge, while in the filled model, separation occurs not at the leading edge but on the blade surface.

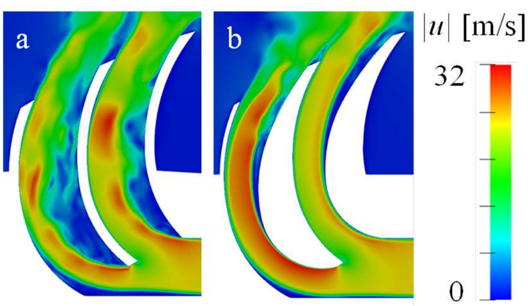

Figure 2. Instantaneous value of magnitude of velocity of (a) original model and (b) filled model.

Figure 3 shows the distribution of the pressure $\boldsymbol{p}$ for each model at time t = 2.1 × 10^{-1} s. Particularly low-pressure regions are present. This corresponds to the vortex region. Comparing the two models, the vortex sizes are very different.

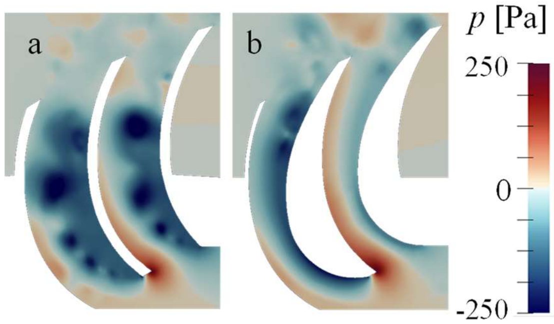

Figure 3. Instantaneous value of pressure of (a)original model and (b)filled model.

POD Analysis of Pressure on Suction Surface

According to Curle (1955), with some assumptions, the sound generated by an object in the flow obeys

$$p_a = \frac{1}{4\pi c}\frac{x_i}{|\boldsymbol{x}|^2}\frac{\partial}{\partial t}F_i \qquad (3)$$

where p_a is the sound pressure, c is the sound speed that is set to 340 m/s, $\boldsymbol{x}$ is the position vector from the object to the observer, and $\boldsymbol{F}$ is the force acting on the object, generated by the flow. This equation says that the temporal derivative of the $\boldsymbol{F}$ is proportional to the sound level.

Considering vortices between blades mainly interfere with the suction surface, force acting on the suction surface was assumed to be the representative of $\boldsymbol{F}$. For further simplicity, pressure fluctuation on the centerline of the suction surface was analysed instead of pressure fluctuation on the whole area of the suction surface. Figure 4 shows the data sampling line. s is the nondimensionalized coordinate on the suction surface.

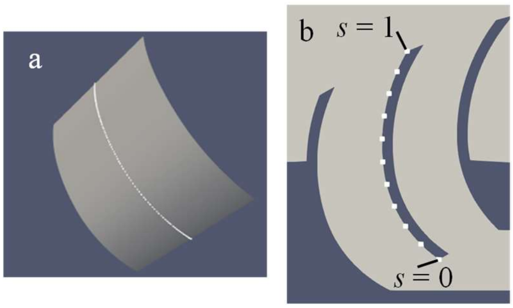

Figure 4. (a) sampling line on the suction surface.
(b) definition of s.

POD analysis was performed on the sampled fluctuating pressure. Figure 5 shows POD modes 1 to 4 of each model. From figure 5(a), modes 1 and 2 show similar spatial scale fluctuation, as do modes in figure 5(b) to (d). Generally, it is known that POD analysis of a temporally periodic signal can compute spatially similar structures as modes in pairs with a phase shift of $\frac{\pi}{2}$. This is much the same as needing cosine as well as sine to represent a traveling-wave of a certain frequency. Thus, these POD modes are considered to represent a single coherent scale fluctuation in pairs. Hereafter, the scale represented by modes 1 and 2 is referred to as "scale a", and the scale represented by modes 3 and 4 as "scale b", etc.

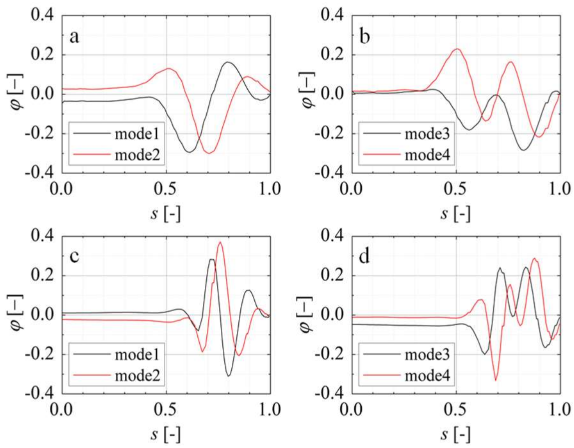

Figure 5. POD modes of fluctuating pressure on the suction surface. (a) modes 1, 2 and (b) modes 3, 4 of the original model. (c) modes 1, 2 and (d) modes 3, 4 of the filled model.

Extract of Vortices at Each Scale

Using some POD modes, fluctuating pressure which contains fluctuation of arbitrary spatial scales can be reconstructed. For example, by integrating the pressure fluctuations, reconstructed from mode 1 and mode 2, with respect to s, a time series of the force F_a acting on the suction surface due to the fluctuation of "scale a" can be calculated. Here, this is an imaginary one-dimensional force that ignores the curvature of the suction surface. Using them as reference signals, conditional averaging of pressure field between blades were performed. Figure 6 shows the conditionally averaged pressure field p_c of each model. Condition is "the forces F_i ($i = a$ and d) take positive peak values". The white point is the reattaching point of the flow where vortices collide with the blade on average. The positive and negative pressure fluctuations seen in the figure represent the vortices at each scale (Observation of the streamlines confirmed that these fluctuations are vortices, which is omitted here).

Generated Sound by Vortices at "Each Scale"

As mentioned above, according to Curle's equation, the generated sound is proportional to the temporal derivative of the force acting on the blade surface. Therefore, the variance of the derivative of F_i ($i = a, b, \cdots$) gives an indication of the sound level produced by the vortex at each scale fluctuation. Figure 7 shows the variance of the derivatives of the forces F_a to F_g and of the F_{all} which is the sum of the forces produced by the vortices at all fluctuation scales. The figure shows that

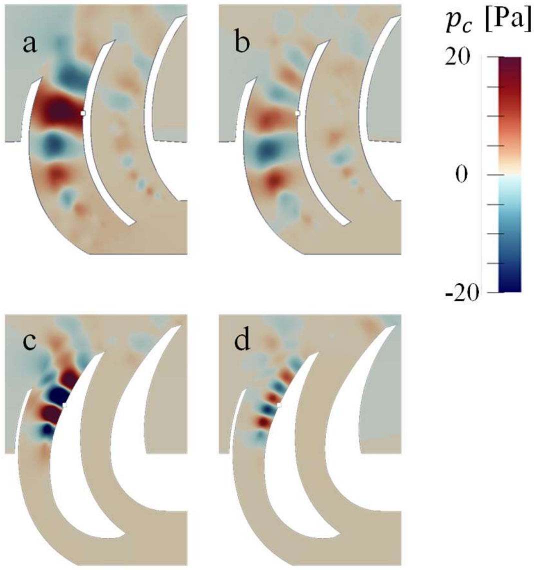

Figure 6. Conditionally averaged pressure p_c of the original model (a, b) and the filled model (c, d). Reference signals are F_a for (a) and (c), and F_b for (b) and (d). Condition is "reference signal takes positive peak values".

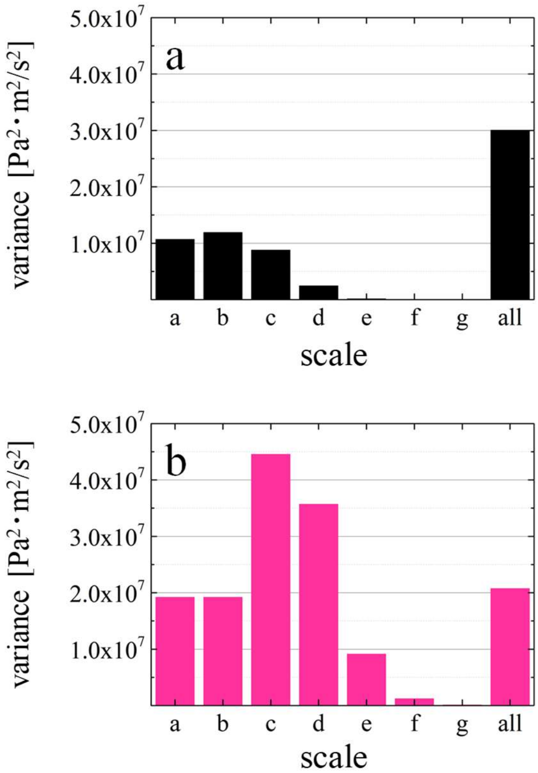

Figure 7. Variance of derivative of F_i of (a)original model and (b)filled model.

the sum of the variance from each scale fluctuation does not match the variance from all scale fluctuations, which is particularly noticeable for the filled model. This is because each F_i are correlated and cancel each other. Therefore, if this cancellation can be controlled, it may lead to quieter fans.

CONCLUSIONS

LES calculations were performed using two types of blade models with different blade thicknesses to simulate separated and reattaching flows. Pressure fluctuations were extracted along the spanwise centerline of the suction surface, and POD analysis was performed. The results showed that two consecutive modes represent the variation generated by one scale coherent motion (which correspond to the vortex). This was supported by the results of the conditionally averaged pressure field using F_i , calculated from the pressure fluctuations reconstructed using two consecutive modes representing "scale i", as a reference signal. The variance of the derivative of F_i is indicator of the sound generated by the vortex at "scale i", but the sum of the variance of F_i did not agree with the variance of F_{all} (which correspond to the sound generated by the vortices at all scales). This indicates that the F_i are correlated and cancel each other, and if this can be controlled, quieter multi-blade fans can be achieved.

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