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# Flow characteristics in a cross-flow fan and its control using sinusoidal protrusions

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**Abstract:** The flow characteristics in a cross-flow fan is investigated using large eddy simulation with an immersed boundary method. The Reynolds number is 5,400 based on the blade chord length and the blade tip velocity at its outer radius. Due to the rotation of cross-flow fan, an eccentric vortex locates at the lower right corner inside the fan, and the main flow passes by this vortex. Most of the efficiency comes from the flow in the lower left corner of the fan, but the flow on the upper part mainly separates, providing lower efficiency. With the protrusion installed on the leading edge of each blade, the flow separation in the upper part is significantly reduced, increasing the fan efficiency by 6.4 %.

*Keywords:* Cross-flow fan, protrusion, eccentric vortex, leading-edge separation.

## 1 Introduction

Cross-flow fans are widely used for air conditioners and ventilators, because one can easily obtain a desired flow rate by increasing the span length even if the radial size is limited. Eck [1] for the first time investigated the flow inside a cross-flow fan using a flow visualization and found a line vortex, which was called an eccentric vortex since its core was eccentric to the axis of impeller rotation. His exceptional study showed that the eccentric vortex determines the characteristics of the flow inside the cross-flow fan, from which people started to study on the flow characteristics. Eck [1] also observed that a flow through the fan, which is called through flow, is induced because the vortex is not placed at the center of the fan. However, it was too complicated and expensive to manufacture a fan with an internal structure so that it was not widely used. Thereafter, Eck [1] found that the vortex can be stabilized without an internal structure if a properly shaped casing, called a stabilizer, is used.

After Eck’s study, diverse researches have attempted to seek for an analytic model based on potential theory, which predicts the flow characteristics inside a cross-flow fan and its performances. Nonetheless, the models were not very accurate, or they required too many empirical relations so that researchers turned their attention to experimental and numerical investigations. In addition, many studies have aimed to improve the fan performances [2, 3].

However, experimental approaches such as PIV (particle image velocimetry) have been rarely used, and most numerical studies have been based on two-dimensional RANS (Reynolds averaged Navier-Stokes) equation which is not sufficient to predict turbulent flow characteristics inside cross-flow fans. Moreover, attempts to enhance their performances have not been entirely based on understandings of flow characteristics. Therefore, in the present study, we conduct LES (large eddy simulations) to predict the flow inside a cross-flow fan and investigate its characteristics together with the variation of the torque coefficient of each blade in the azimuthal direction. From this analysis, we identify losses in the flow and adopt leading-edge protrusions inspired by humpback whale’s tubercle

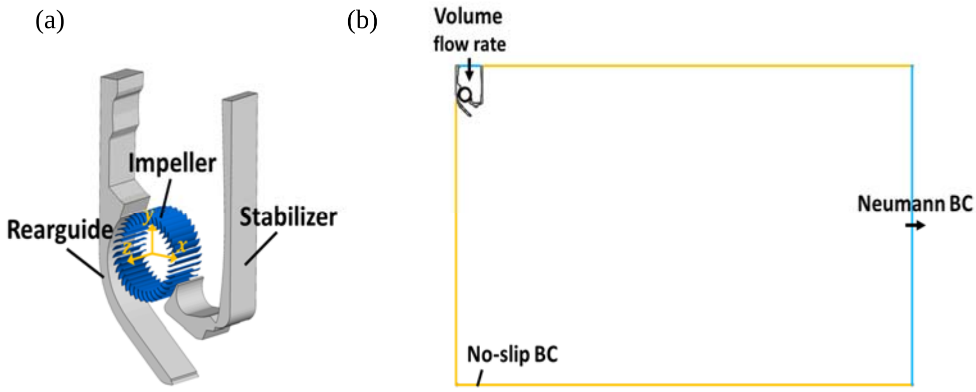


Figure 1: (a) Schematic diagram of a cross-flow fan; (b) computational domain and boundary conditions.

structures to improve the efficiency of a cross-flow fan.

## 2 Numerical Details

We solve the three-dimensional, unsteady, incompressible continuity and Navier-Stokes equations in a Cartesian coordinate and perform LES with a dynamic global model [4]. A 2$^{nd}$-order fully implicit fractional step method is used to solve the spatially filtered equations, and a 2$^{nd}$-order linearization method [5] is applied. Also, an immersed boundary method [6] is used to satisfy the no-slip boundary conditions on the fan.

Figure 1 shows a schematic diagram of a cross-flow fan, which includes an impeller, a stabilizer and a rear guide, together with the computational domain. The impeller has 37 blades, and its diameter is 7.2$c$, where $c$ (= 13.1 mm) is the blade chord length. Its rotational speed is 1,250 rpm and the corresponding Reynolds number is 5,400 based on the blade chord length and the blade tip velocity at the outer radius. A constant volume flow rate is given at the inflow region, and the Neumann boundary condition is imposed at the outflow region. Moreover, a sponge layer, which uses a 1:2:1 filter [7], is implemented at the outflow region to dissipate convecting vortices so that simulations could be conducted stably. The periodic and no-slip boundary conditions are given, respectively, in the spanwise direction and on the remaining boundaries. For the impeller with the base blade configuration (figure 2 (a)), the size of the computational domain is 250$c$ ($L_x$) × 150$c$ ($L_y$) × 4$c$ ($L_z$), and the number of grid points used is 913 ($x$) × 1036 ($y$) × 51 ($z$). As a passive control device, we introduce a sinusoidal protrusion on the leading edge of each blade inspired by humpback whale tubercle structures [8, 9], where the wavelength of the protrusion is 1.67c. Figure 2 (b) shows a modified blade with a sinusoidal protrusion. For the modified blade, the size of the computational domain is 250$c$ ($L_x$) × 150$c$ ($L_y$) × 1.67$c$ ($L_z$), and the number of grid points is 913($x$) × 1036($y$) × 21($z$).

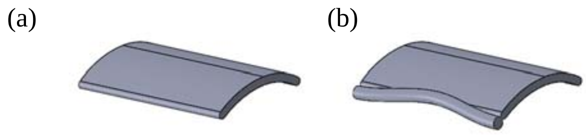


Figure 2: (a) Base blade; (b) blade with a sinusoidal protrusion on the leading edge of each blade.

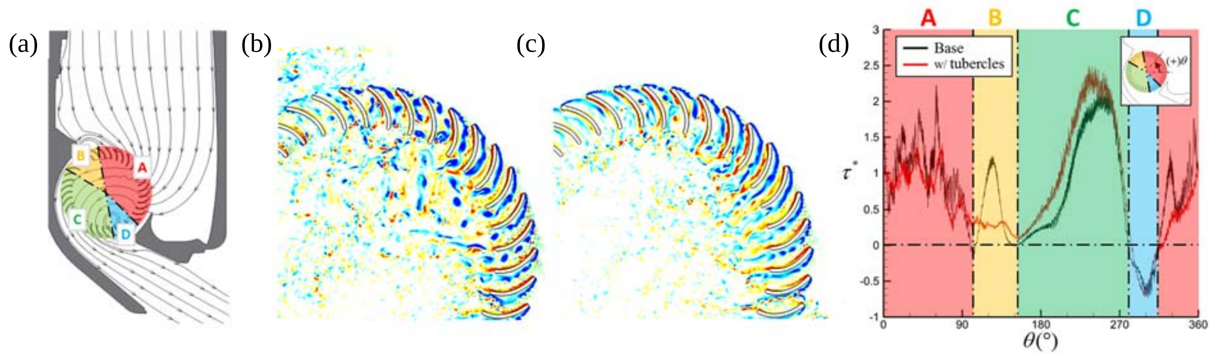


Figure 3: flow characteristics and torque coefficient with and without protrusion: (a) phase averaged streamlines; (b and c) contours of the spanwise vorticity without and with protrusion, respectively; (d) torque coefficient along the azimuthal direction;

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# 3 Results

Figure 3 (a) and (b) shows the flow characteristics across the base cross-flow fan. A vortex exists at the lower right corner of the cross-flow fan, as observed from previous studies [2, 3]. Based on the torque variation, we identify four regimes in the azimuthal direction (A to D; Figure 3 (a)). In particular, flow separation occurs from the leading edges of the blades in regime A (Figure 3 (b)), together with highly oscillatory variation of the torque coefficient (Figure 3 (d)).

The fan efficiency is defined as the rate at which the input torque ($\tau\Omega$) is converted to the output pressure rise ($\Delta p_t Q$). Thus, higher positive torque is desirable if the torque is well converted to the pressure rise. Otherwise, high positive torque lowers the fan efficiency. Therefore, only a small amount of work can be done by a blade even if high positive torque is acting on it, and thus it is necessary to analyse the flow field around the blade to determine how well the fan works.

In regime C, it is observed that fluid velocity is greatly accelerated, and the flow direction changes significantly. This means that a large amount of work is done by the blade to the fluid and the highest positive peak of torque occurs in this regime. In regimes A and B, local peaks of positive torque are also observed, but corresponding flow fields show that those peaks are associated with proper work. In other words, those high torque is not well converted to pressure rise in these regimes. Especially, massive flow separations are observed in regime A (Figure 3 (b)), which deteriorates the fan efficiency. With a sinusoidal protrusion on the leading edge, the separations and the torque oscillation are considerably reduced (Figures 3 (c) and (d)), which improves the fan efficiency by 6.4%.

# 4 Conclusions

In the present study, we examine flow characteristics inside a cross-flow fan and a flow control method inspired by humpback whale. By analyzing flow fields and a torque coefficient graph, four regimes in the azimuthal direction with different flow characteristics are recognized. Moreover, the separation of the upper part is pointed as the main reason for reducing the fan efficiency. Finally, a passive flow control method motivated by humpback whale flipper's tubercle structure is used, and the fan efficiency is enhanced by 6.4%.

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