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병진운동하는 평판의 모서리에서의 3차원 와류 구조 가시화

김대겸†

Three-dimensional vortex structure near a corner of a translating plate

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Abstract. Three-dimensional vortex structures in the corner region of translating normal plates are visualized experimentally with defocusing digital particle image velocimetry. Vortex formation processes for three plates with corner angle 60°, 90°, and 120° are compared in order to study the effect of corner shape on vortex formation. In all cases, the self-induction of the starting vortex and its interaction with the potential flow induced by the moving plate cause the vortex to change its form dynamically after the plate starts to translate. While the vortex near a corner follows the plate in the low corner angle of 60°, the vortex separates early from the plate and its forward motion becomes slow in the high corner angle of 120°. It is also found that the starting vortex can transport inward at the corner, which depends on the corner angle.

Key Words : Defocusing DPIV, 3D PIV, Vortex structure(와류 구조), Vorticity transport(와도 이동), Corner flow(모서리 유동)

1. Introduction

Vortex formation by objects starting from rest has been one of the popular topics in vortex dynamics. The roll-up process of starting vortex sheets is commonly used to explain lift generation in a starting airfoil.[1] Moreover, the starting vortex formation of various two-dimensional models has been studied.[2-5] The formation process of the starting vortex drawn attention recently because of vortex-related optimization principles in biological propulsion and transport.[6-8] While two-dimensional and axisymmetrical starting vortices have been studied extensively, experimental studies of three-dimensional starting vortices by moving objects of low aspect ratio are sparse.[9,10] In particular, in spite of its importance in understanding vortex dynamics of a moving body of low aspect ratio, three-dimensional flow in a corner region has been rarely studied due to the lack of techniques that could provide quantitative three-dimensional mapping of complex flows. In this paper, we experimentally study vortex formation in the corner region of impulsively translating thin plates with a 90-degree angle of attack by using a three-dimensional flow measurement technique. The complicated flows near the corners of translating plates are investigated in order to understand the effect of a corner angle on the morpho-dynamics of the starting vortex.

2. Experimental method

In order to map three-dimensional fields near a corner of a translating thin plate, a defocusing digital particle image velocimetry system (DDPIV) was used.[11-13] A simple schematic of the experimental setup is shown in Fig. 1. A DDPIV camera was placed in front of a water tank (870 × 430 × 360 mm^3). The water tank was seeded with 100㎛ silver-coated particles. An acrylic plate with 1.65 mm thickness was immersed vertically so that a corner region is included in the measurement volume of the DDPIV camera. Three plates with

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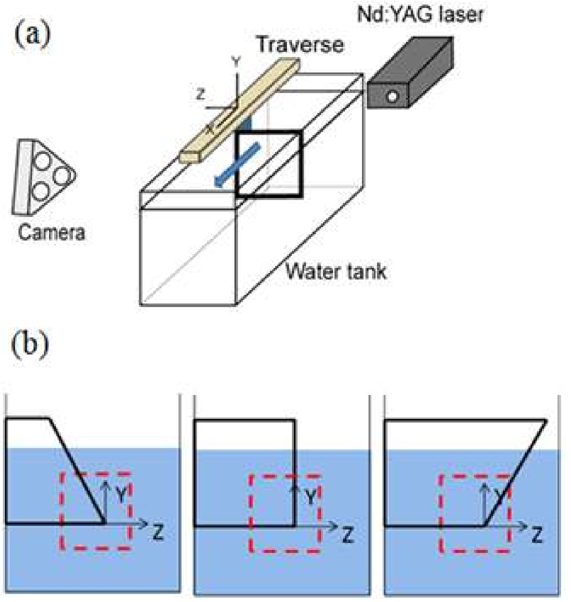

Fig. 1. (a) Schematic of the experimental setup. The arrow indicates the moving direction of the plate model. (b) Positions and shapes of the plates (60°, 90°, and 120°). The dashed lines are the volume in which the flow field is measured.

different corner angles (60°, 90°, and 120°) were used. In the 90° angle case, the area immersed in water has height 160 mm and width 200 mm. The position of the corner in the mapping volume is the same for three different corner-angle cases. The vertical edge on the other side of the plate was closely aligned with the tank wall to avoid water leakage through a gap. Even though we used the plates with finite length, ideally there should be no characteristic length so that the vortex formation processes are dependent only on corner shapes. The plates accelerated for 1 sec to start, and translated with a constant velocity of 20 mm/sec; the Reynolds number based on the constant velocity and the height of immersed plates is 3200. The images taken from the camera with 5 image pairs/sec were processed using a DDPIV software. In order to obtain a velocity field, a relaxation method of 3D two-frame particle tracking was used.13 Then, vorticity fields were obtained from the velocity fields using central difference method. Because of the limitation of the camera measurement volume size, only the flow near a corner region was mapped. Another set of the experiment was performed by translating the initial position of the plate 120 mm in the direction parallel to the camera front face. The total fluid volume measured by the two sets of the experiment was 280 × 140 × 140 mm^3.

3. Results and Discussion

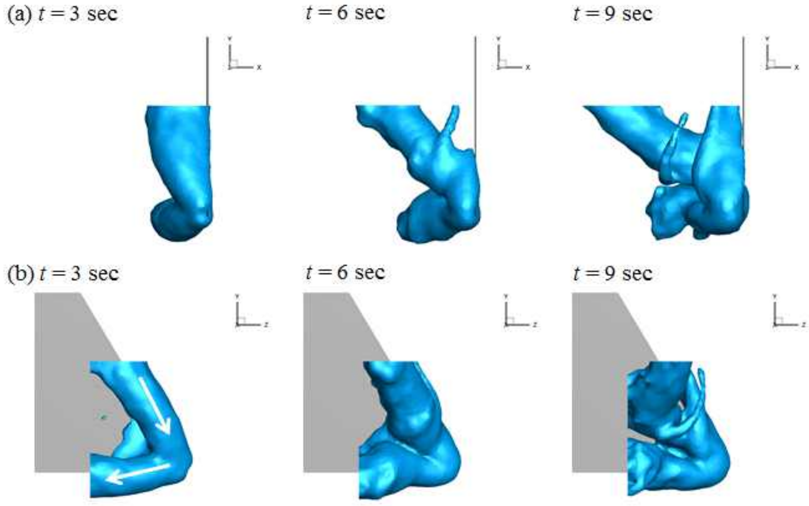

Fig. 2. Vortex formation process at the corner of the 60° corner-angle plate. (a): side view from the +*z* axis and (b): back view from the -*x* axis. Iso-surfaces of vorticity magnitude ($|\omega|$ = 1.7/sec) are used. The white arrows show the rotating direction of the vortex with the right-hand rule.

Figs. 2-4 show vortex formation process near the corner of the plate with a different corner angle (60°, 90°, and 120°). In these figures, iso-surfaces of vorticity magnitude were used to represent vortex structures. A relatively high vorticity magnitude was chosen to show a vortex core clearly. At start, vortex sheet rolls up along the plate edge. Therefore, the shape of the vortex is similar to the shape of the plate edge. However, as the plate moves farther, the vortex core begins to separate non-uniformly from the edge and finally lose its initial shape. After the vortex core separates from the edge, newly-created vortex sheets continue to roll up around the deformed vortex core. Here, the term, vortex separation, is used to indicate that a vortex core does not follow the plate edge and retards its forward motion.

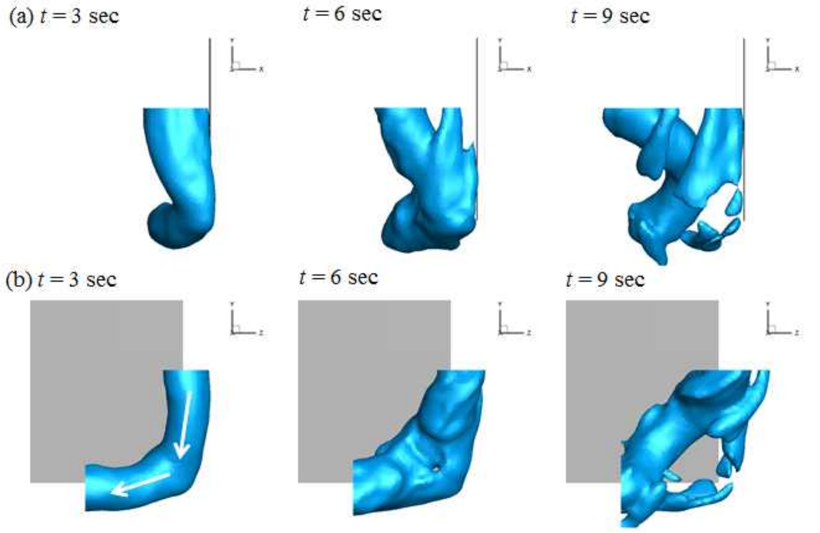

Fig. 3. Vortex formation process at the corner of the 90° corner-angle plate. (a): side view from the +*z* axis and (b): back view from the -*x* axis. Iso-surfaces of vorticity magnitude ($|\omega|$ = 1.7/sec) are used. The white arrows show the rotating direction of the vortex with the right-hand rule.

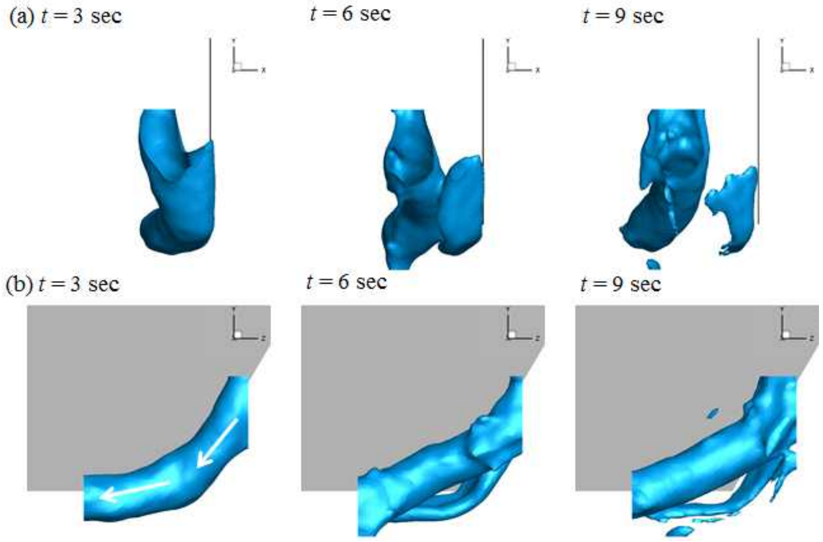

Fig. 4. Vortex formation process at the corner of the 120° corner-angle plate. (a): side view from the +*z* axis and (b): back view from the -*x* axis. Iso-surfaces of vorticity magnitude ($|\omega|$ = 1.7/sec) are used. The white arrows show the rotating direction of the vortex with the right-hand rule.

As can be seen in (a) of Figs. 2-4, the corner angle affects the morphology of the corner vortex. As the corner angle is small (60°), the vortex close to the vertex of the plate follows the forward motion of the plate without noticeable separation from the edge. Meanwhile, the vortex far from the corner vertex separates from the corner early. This trend is weakened as the corner angle becomes larger. For the 120° case (Fig 4(a)), the corner vortex tends to separate from the corner earlier than that of the lower angle cases. Its x-directional position is quite uniform.

If there is a thin vortex tube in a flow field without a moving object, the vortex tube can change its position by its self-induction. As the curvature of the thin vortex tube gets bigger, the vortex tube has the larger self-induced velocity component in the direction bi-normal to the curved vortex tube.14 This theory can be used in explaining the dependence of the vortex forward motion on the corner angle. As the corner angle becomes smaller, the curvature of the corner vortex becomes larger. Therefore, the vortex of the smaller corner angle can have larger induced velocity in the direction bi-normal to the plate edge, x-direction in our model.

It is well known that, in the absence of a moving object, the velocity field in the fluid domain can be obtained from the vorticity induction equation. This approach makes it easier to explain self-induction of a vortex or mutual interaction with other vortices. However, in the case of a vortex near a moving body in an infinite field, the potential flow effect caused by a moving body should be taken into consideration as well because the velocity field must be constructed from both vorticity distribution and potential flow caused by the plate motion.[14] Thus, self-induction of the vortex is not enough to explain the morpho-dynamics of the vortex generated by the plate. For example, when the plate just starts to translate, the starting vortex follows the plate motion in spite of its small strength. However, the vortex gradually separates from the plate and retards its forward motion even though its strength becomes larger as the plate continues to translate. Thus, in order to fully understand the vortex motion behind the plate, the potential flow effect of the plate motion should be considered. While the plate translates, fluid close to the back of the plate are under strong potential flow effect enough to follow the plate motion. As the distance between the fluid elements and the plate becomes larger, the potential flow induced by the plate becomes smaller. For this reason, it is difficult for the vortex, which is far from the plate, to follow behind the moving plate.

As well as the forward motion of the corner vortex, the inward motion of the corner vortex is also different among the three corner-angle cases studied here ((b) of Figs. 2-4). As the plate starts to translate, a low pressure region is generated behind the plate and an inward potential flow (the flow from the outside toward the backside of the plate; toward the negative z-axis and the positive y-axis) is induced behind the plate. Due to this low pressure region just behind the plate, the corner vortex can move inward gradually. The corner vortex of the 90° case shows more distinct inward motion than that of the 120° case. In the 60° corner-angle case, the vortex near the corner vertex does not move inward noticeably, but stays close to the corer.

4. Concluding remarks

The flow structure near a corner of a translating plate whose surface is normal to its moving direction was visualized with three-dimensional flow measurement technique, Defocusing DPIV. The vortex structure near a corner depends on the angle of the corner, and the three cases of this study show significant difference in the development of the vortex structure near the corner. The morpho-dynamics of the corner vortex are strongly affected by its self-induction and the potential flow of the translating plate. This fundamental study will be helpful to better understand the flow patterns of a moving object with complex geometry.

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