Detailed Wake Structure behind Unsteady Airfoils and Characteristics of Dynamic Thrust

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Abstract. The detailed vortex flow structures behind an unsteady airfoil in pitching and heaving motions at low Reynolds number regions have been measured by PIV measurement. Moreover, the dynamic thrust measurements on an airfoil have been performed by a six-axes sensor in a water tunnel. An unsteady airfoil forms thrust producing vortex streets with vortices accompanied with large vorticities, without disturbing flow around an airfoil. In the wake of an unsteady airfoil at $\varphi = \pi/3$ and π, jet velocity becomes over 2.0. The thrust efficiency increases drastically with increase of Strouhal numbers and reaches its maximum value at around St = 0.2, then decreases gradually. The maximum thrust efficiency is $\varphi = \pi/2$ and is approximately 0.40.

Key words: unsteady airfoil, thrust, wake, vortex.

1. Introduction

Recently, a few studies on unsteady flows in low Reynolds number regions have been attracting attentions since the Micro-Electro-Mechanical-Systems (MEMS)) has been improved with the aim of flow control and development of Micro-Air-Vehicle (MAV). Moreover, a study on vortex flow behind an unsteady airfoil in a low Reynolds number region has been reported. Triantafyllou clarified that oscillating foils produce thrusts through development of jet-like average flow [1]. Anderson measured fluid forces and mapped flow around a harmonically oscillating foil at zero average angle of attack [2]. Lai and Platzer revealed that vortex flow patterns change from a drag producing type to a thrust producing type as non-dimensional plunging velocity increases [3]. Fuchiwaki and Tanaka showed vortex flow patterns and jet characteristics behind a pitching airfoil and a heaving airfoil [4]. Lewin presented a numerical model for two-dimensional flow around an airfoil undergoing heaving motions in viscous flow [5]. Fuchiwaki and Tanaka have also reported characteristics of dynamic thrusts acting on a pitching airfoil and a heaving airfoil [6]. However, detailed vortex flow structures and relationships between characteristics of dynamic forces acting on an unsteady airfoil in pitching and heaving motions and vortex flow structures at a low Reynolds number region have not been clarified sufficiently.

In this study, the authors have measured detailed wake structures behind an unsteady airfoil in pitching and heaving motions at low Reynolds number regions by PIV measurement. Moreover, the authors have performed dynamic thrust measurements on an airfoil by a six-axes sensor in a water tunnel. The result clarified not only details of vortex flow structures but also relationships between characteristics of dynamic thrusts and details of vortex flow structures.

2. Experimental Setup and Experimental Conditions

The experimental apparatus for PIV measurement consisted of a water tunnel, a test airfoil, an equipment to generate combined motions of pitching and heaving motions, a water-cooled Argon-Ion laser, a plane mirror, a high-speed camera and tracer particles [4]. The experimental apparatus for measurements of dynamic thrusts consisted of a water tunnel, an equipment for to generate a combined motion of pitching and heaving, a test airfoil and a six-axes sensor [6].

The airfoil used for the test was NACA0010 (c = 0.06 m, l = 0.20 m). Unsteady motion was given to sinusoidal waves and phases were given to the motions. Strouhal number based on the total amplitude of the trailing edge was defined as Equations (1). The mean angle of attack is 0 degree. The Reynolds number based on chord length is 40000.

$$St = \frac{2bf}{V_0} \tag{1}$$

3. Results and Discussion

3.1. VORTX FLOW PATTERNS AND VORTICITY CONTORS BEHIND AN UNSTEADY AIRFOILS

Figure 1 shows vorticiy contour maps of an unsteady airfoil obtained at St = 0.45. Figures 1 (a), (b) (c) and (d) show results from the conditions $\varphi = \pi/3$, $\pi/2$, π and $3\pi/2$ respectively. The clear thrust producing vortex streets are formed in the wake of the airfoil. Furthermore, for $\varphi = \pi/3$ and $3\pi/2$, vortices are arrayed with closed intervals however for $\varphi = \pi/2$ and π the vortex intervals are rarefactional. Moreover, for $\varphi = 3\pi/2$, vortices roll at the leading edge of the airfoil and the flow around the airfoil is turbulent significantly. It has been reported that thrust producing vortex streets are formed at a Strouhal number of around 0.45 in airfoil wakes accompanied with independent motions of pitching and heaving [4]. However, in the case of an independent motion of pitching, vorticities of the vortices forming thrust producing vortex streets are small and the flow field around the airfoil becomes turbulent due to vortices rolling up at the front edge. It has been found that by combining pitching and heaving motion, it is possible to form thrust producing vortex streets with vortices accompanied with large vorticities, without disturbing flow around an airfoil, comparing to airfoils with independent pitching and heaving motions.

3.2. JET VELOCITY BEHIND AN UNSTEADY AIRFOILS

Figure 2 shows mean values for one motion cycle in velocity distributions at the point one cord length behind the unsteady airfoil at St = 0.45. The non-dimensional velocity over 1.0 indicates the jet velocity. The jet flow is generated in the wake. In particular, jet flow becomes over 2.0 at $\varphi = \pi/3$ and π and the values are greater than those of the heaving airfoil [4]. This is because thrust producing vortex streets are formed by vortex with large vorticities.

3.3. DYNAMIC THRUST ACTING ON UNSTEADY AIRFOILS

Figure 3 shows mean values for one cycle of unsteady thrusts on an unsteady airfoil for which pitching and heaving motions are combined. The dynamic thrusts increase with increase of St. Specifically, for $\varphi = \pi/3$ and $\pi/2$, large thrusts are produced. This result may be judged appropriate since enhanced flow over 2.0 is generated in the wake in the result of Figure 2. On the other hand, for $\varphi = 0$, $3\pi/2$, $5\pi/3$ and $11\pi/6$ thrusts tend to decrease with increase of St.

3.4. THRUST EFFICIENCY OF UNSTEADY AIRFOILS

Figure 4 shows thrust efficiency of an unsteady airfoil for which pitching and heaving motions are combined. The thrust efficiency increases drastically with increase of Strouhal numbers and reaches its maximum value at around St = 0.2, then decreases gradually. It is well known that Strouhal numbers of aquatic animals when they swim are around St = 0.2. In our experimental result from rigid airfoils, the maximum efficiency is obtained at around St = 0.2. Moreover, the maximum thrust efficiency is $\varphi = \pi/2$ and is approximately 40%. From the result shown in Figure 3, significantly large thrusts are produced on an unsteady airfoil however at the same time large lifts and moments are generated therefore thrust efficiency becomes small. For $\varphi = \pi/2$, thrust efficiency becomes increase not only because large thrusts are produced on an unsteady airfoil but also because lifts and moments are relatively small. Maximum thrust efficiency for an independent motion of heaving was 20% and that of a pitching motion was 34% [6]. Thrusts efficiency increased slightly by combing pitching and heaving motions however significant increase was not observed.

4. Conclusions

An unsteady airfoil in pitching and heaving motions forms thrust producing vortex streets with vortices accompanied with large vorticities, without disturbing flow around an airfoil, comparing to airfoils with independent pitching and heaving motions. In the wake of an unsteady airfoil at $\varphi = \pi/3$ and π, jet velocity becomes over 2.0. The dynamic thrusts increase with increase of

Strauhal number. Specifically, for $\varphi = \pi/3$ and $\pi/2$, large dynamic thrusts are produced. The thrust efficiency increases drastically with increase of Strouhal numbers and reaches its maximum value at around St = 0.2, then decreases gradually. The maximum thrust efficiency is $\varphi = \pi/2$ and is approximately 0.40.

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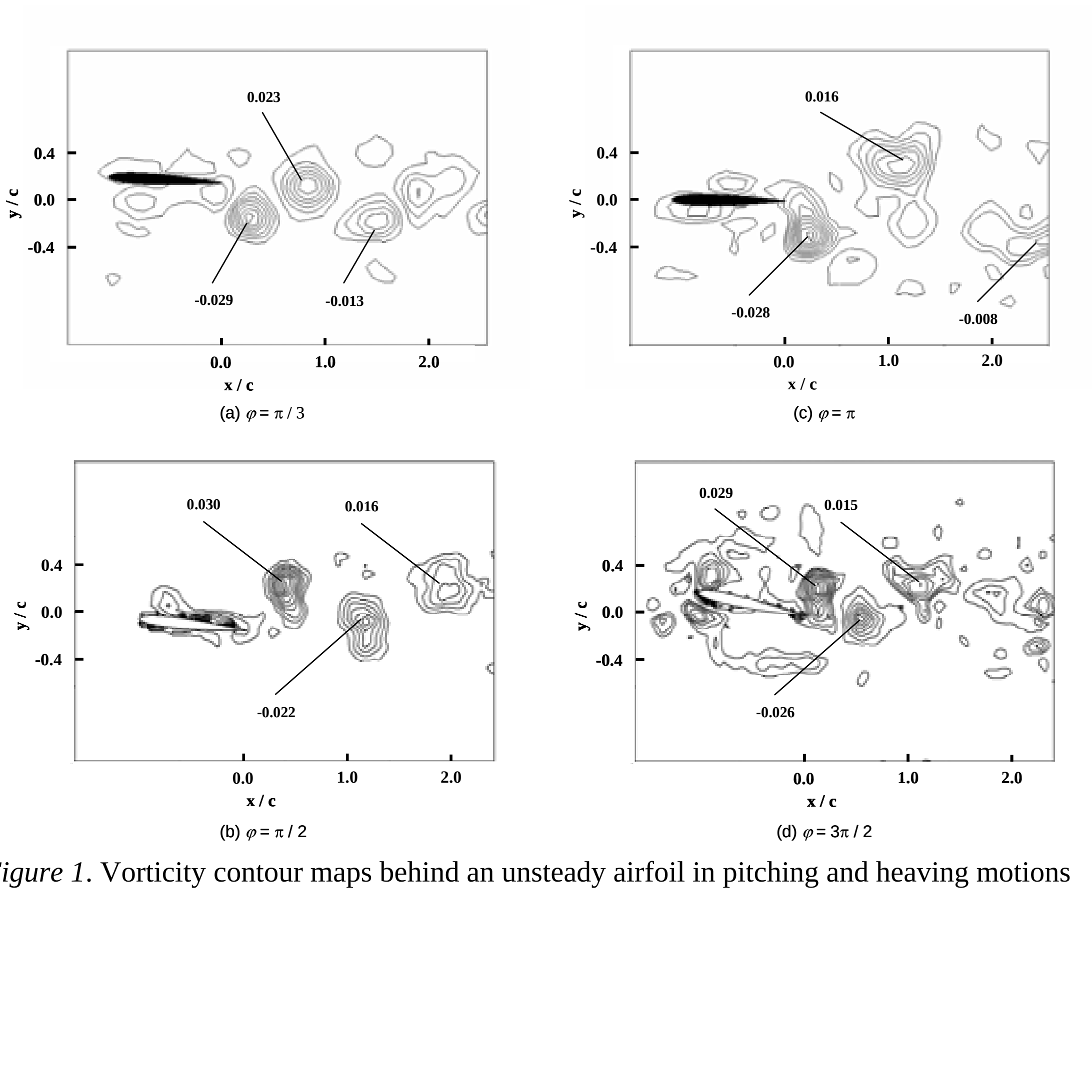

Figure 1. Vorticity contour maps behind an unsteady airfoil in pitching and heaving motions

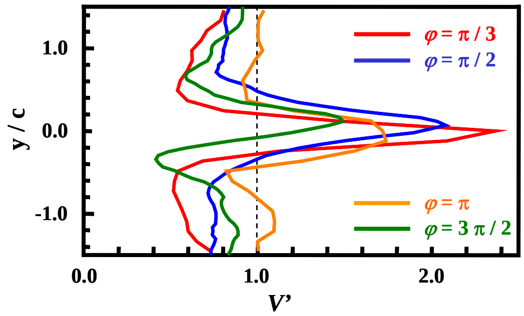

Figure 2. Mean values for one motion cycle in velocity distributions at the point one cord length behind the unsteady airfoil in pitching and heaving motions

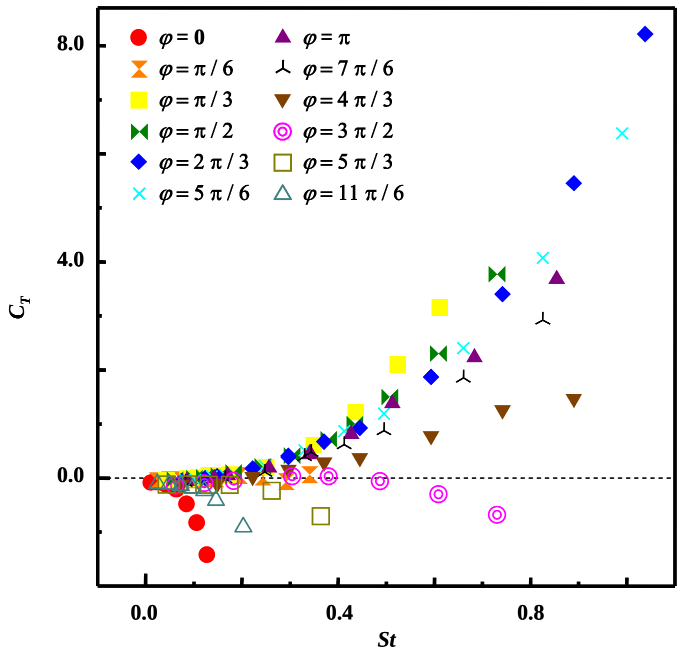

Figure 3. Mean values for one cycle of dynamic thrusts on an unsteady airfoil in pitching and heaving motions

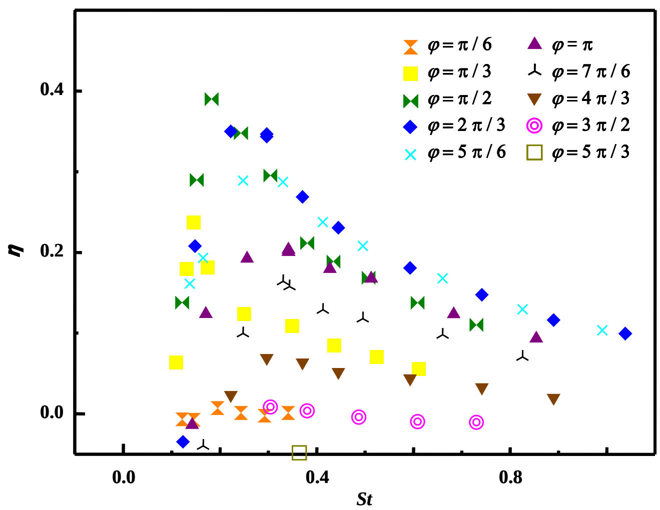

Figure 4. Thrust efficiency of an unsteady airfoil in pitching and heaving motions