Unsteady hydrodynamic forces acting on a robotic arm and its flow field during the crawl

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Abstract—This study aims to clarify the mechanisms by which unsteady hydrodynamic forces act on the hand of a swimmer during a crawl stroke. Measurements were performed for a hand attached to a robotic arm with five degrees of freedom in-dependently controlled by a computer. The computer was pro-grammed so the hand and arm mimicked a human performing the stroke. We directly measured forces on the hand and pres-sure distributions around it at 200 Hz; flow fields underwater near the hand were obtained via 2D particle image velocime-try (PIV). The data revealed two mechanisms that generate unsteady forces during a crawl stroke. One is the unsteady lift force generated when hand movement changes direction during the stroke, leading to vortex shedding and boundary vortex created around it. This boundary vortex circulation re-sults in a lift that contributes to the thrust. The other occurs when the hand linearly moves with a large angle of attack, cre-ating a Kármán vortex sheet. This sheet alternatively sheds clockwise and counterclockwise vortices, resulting in a quasi-steady drag contributing to the thrust.

Key words: Competitive swimming, Flow visualization, 3D PIV

1. Introduction

The importance of unsteady phenomena in human swimming has been emphasized in previous studies (Sanders, 1999; Toussaint et al., 2002) , hence we know that quasi-steady hydrodynamic theory is insufficient to describe the mechanisms by which humans propel themselves through water. To address such problems, computational fluid dynamics (CFD), including the effects of unsteady fluid flow, has been making a major contribution to understanding hydrodynamic phenomenon when the swimmer was moving actively either on the surface or underwater (Von Loebbecke et al., 2009; Dabnichki, 2011). Particle image velocimetry (PIV) has also proven to be a powerful tool for measuring the actual flow fields around human swimmers. Based on PIV measurements, Matsuuchi et al. (2009) have reported that a pair of counter-rotating vortices might play an important role in generating unsteady fluid forces, and Hochstein and Blickhan (2011) have found that vortices generated in the region of strongly flexing joints are suitable to enhance propulsion; this process is known as vortex re-capturing. Combining the results from CFD and PIV should help in visually and theoretically understanding complicated hydrodynamic mechanisms. However, actual experiment data, such as for forces and pressures, are also valuable for verifying CFD results and interpreting PIV images. Therefore, in a previous study, we conducted experiments in which we directly measured hydrodynamic forces, pressure distributions, and flow fields around a hand attached to a robotic arm (Takagi et al., 2013). In that work, simple 2D hand motions were the subject for study; nevertheless, a significant unsteady hydrodynamic phenomenon was observed that reveals the behavior of certain kinds of vortices play an essential role in generating substantial unsteady hydrodynamic forces. In this study, we used a robotic arm and PIV to clarify the mechanisms by which unsteady forces are generated during 3D crawl-stroke-motions. By analyzing the 3D motions, it is expected that actual propelling mechanisms can be elucidated and the findings will contribute to an improvement of swimmers' technique.

2. Method

2.1. Robotic arm and hand models

A robotic arm that consisted of a trunk, shoulder, upper arm, forearm, and hand (Takagi et al., 2013) was used. The robotic arm had five degrees of freedom (DOF), which were driven by three motors housed in the trunk and two motors housed in the upper arm and forearm.

Two hand models were fabricated from a silicon-based material (Takagi et al., 2013). One hand (*Hand 1*) was used to measure hydrodynamic forces via flow vi-

the leading edge was the little-finger-side, and the resultant flow (**V**) was inward from the little-finger-side, as shown in the figure. Since the lift force acts perpendicular to*V*, the lift force must contribute to an increase in the thrust force. This phenomenon is known as the unsteady mechanism of force generation that insects apply for flying (Dickinson, 1996).

In the case of*Stroke I*(lower drawing in Fig. 2), when the hand moved in a linear manner with a large angle of attack, a Kármán vortex street was generated, and clockwise or counterclockwise vortices were alternately shedding from it. At that time, the pressure on the palm side was large and positive, and the pressure difference between the palm and dorsal sides increased, producing a drag force. This drag force must contribute to an increase in the thrust force.

We have been able to unravel parts of the hydrodynamic mechanisms during the crawl stroke, but we also recognize some limitations. For example, the resultant flow vectors relative to the hand (**V**) achieved by the robotic arm did not reach 1.7 m/s at the maximum; in fact, they were approximately half of those in actual swimming motions (Maglischo, 2003). In addition, the robotic arm had no degree-of-freedom at the wrist joint, thus palmar flexion and dorsal flexion of the wrist could not be reproduced. These differences and defects were due to limitations on the output power and driving mechanisms of the robotic arm. Only 2D flow-field images during crawl-stroke-motions were obtained in this study. Since hand movements are 3D, it would be better to obtain 3D vortices and velocity distributions; this has not yet been done due to limitations on the number of CCD cameras and on the performance of the software.

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