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Short communication

Influence of surface penetration on measured fluid force on a hand model

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ABSTRACT

The purpose of this study was to quantify the effect of wave drag due to surface penetration on drag and lift forces (C_d and C_l) acting on a hand model. The values of C_d and C_l had been acquired to gain the hydrodynamic characteristics of the swimmer's hand and predict force on the swimmer's hand. These values have also been used to benchmark computational fluid dynamics analysis. Because the previous studies used a hand/forearm model which penetrated the water's surface, the values of C_d and C_l include the effect of the surface wave on the model. Wave formation causes pressure differences between the frontal and rear sides of a surface-penetrating model as a result of depressions and elevations in the water's surface. This may be considered as wave drag due to surface penetration. Fluid forces due to wave drag on the forearm should not be included in the measured C_d and C_l of a swimmer's hand that does not sweep near the water's surface. Two hand/forearm models are compared, one with the hand rigidly connected to the forearm. The other model was constructed to isolate the fluid forces acting on the hand from the influence of wave drag on the forearm. The measurements showed that the effect of wave drag on the hand model caused large increases in the values of C_d, up to 46–98% with lesser increases in C_l of 2–12% depending on the hand orientation. The present study provides an improved method to determine the values of C_d and C_l that eliminates the effect of wave drag on a hand/forearm model by isolating the measurement of fluid forces on the forearm of the hand/forearm model in order to separately acquire the forces on the hand.

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1. Introduction

The coefficient of drag and lift forces (C_d and C_l) have been calculated from laboratory-based measurements to investigate the hydrodynamic characteristics of the swimmer's hand in a swimming flume or a towing tank (Berger et al., 1995; Sanders, 1999; Schleihauf, 1979) and used for predicting fluid forces acting on the hand in swimming as a quasi-static approach (Berger et al., 1999; Cappaert et al., 1995; Schleihauf et al., 1983). Computational fluid dynamics (CFD) analysis has been developed and applied to research in swimming, especially for fluid forces acting on the hand (Bixler and Riewald, 2002; Rouboa et al., 2006). For CFD analysis, the laboratory-based values of C_d and C_l reported previously were used as a benchmark of the computation.

However, the studies of fluid forces on a hand model in a swimming flume or a towing tank have used models that penetrate the water surface. A surface piercing wrist or forearm is likely to induce wave drag. Passive wave drag on swimmers near the water's surface is more than 50% of total drag at typical competitive swimming speeds, and wave drag on an object is important when moving within twice the object's diameters of the water surface (Vennell et al., 2006). Thus, wave drag acting on the model could affect the magnitudes of C_d and C_l of the hand reported in previous works. Sanders (1999) attempted to correct for wave drag on the forearm by subtracting the fluid forces on an isolated model forearm from the fluid forces on a hand/forearm model and determined C_d and C_l of the hand, but acknowledged that end effects of the isolated model forearm on the measured fluid forces could not be accounted for. Kudo (2008) noted an increase in C_d at one angle due to wave drag. The present study was conducted to further quantify the effect of wave drag acting on a hand/forearm model on C_d and C_l at various orientations with a hand/forearm model constructed to isolate the forces on the hand from those on the forearm.

2. Methods

2.1. Non-isolated hand model

A hand/forearm model of a competitive university swimmer was made of silicone-based material, the shape adopted was with no finger separation and the

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thumb extended in the plane parallel to the palm (Fig. 1). The angle between the thumb and the index finger was approximately 30°. A split plaster mould was constructed, and a stainless steel support somewhat similar to a rigid skeleton of the arm was fabricated to fit within the plaster mould. After placing the stainless steel support in the mould, the silicon was poured into the plaster mould. The area of the hand plane was 0.0148 m^2. Internally wired pressure sensors (10 mm diameter and 3 mm thickness) were embedded in the twelve concavities of the hand surface for a parallel study to establish a new method to predict fluid forces acting on the swimmer's hand (Kudo et al., 2008). The present study did not use any pressure date for the determination of C_d and C_l of the hand.

The non-isolated hand model was attached to a load cell (AMTI, MA, USA) to measure fluid forces acting on the model for 5 s sampling at 100 Hz and was fixed vertically in a swimming flume (E-Type Engineering Ltd., New Zealand). In the calibration procedure of the load cell, the length of the moment arm between the origin of the load cell and the centre of the hand was considered. Fluid forces on the model in two dimensions consisted of two components, drag forces in the same direction as the flow direction in the flume and lift forces perpendicular to the longitudinal axis of the model and the flow direction. The hand part of the model was submerged. The flow speed in the flume was set at 1.5 m/s. The angle of attack, α, was set as an angle about the longitudinal axis and defined as 0° when the on-coming flow to the model was directed to the thumb side and 90° when the on-coming flow to the model was directed to the ventral side. In the measurement of the non-isolated hand model, α was set from 30° to 150° in 30° increments.

The coefficients of drag and lift forces acting on the hand influenced by wave drag (C_{d_w} and C_{l_w}) were calculated by the following equations:

$$C_{d\_w} = \frac{F_d}{(1/2)\rho U^2 A} \tag{1}$$

$$C_{l\_w} = \frac{F_l}{(1/2)\rho U^2 A} \tag{2}$$

where F_d is the measured drag force acting on the model, ρ is the density of water, U is the flow speed in the flume, A is the area of the hand part in the model, F_l is the measured lift force acting on the model.

Fig. 1. The hand and forearm model. Note: the surface of the hand had 12 concavities where internally wired pressure sensors were embedded (10 mm diameter and 3 mm thickness). The pressure data was not reported in the present study.

2.2. Isolated hand model

To measure fluid forces acting on the hand model isolated from a forearm, the following setup was constructed as shown in Fig. 2. (i) The silicon-based forearm part was cut so that the hand part and the stainless steel support remained. (ii) The stainless steel support for the hand model was covered with a hollow cylindrical "forearm" that was attached rigidly above the side of the load cell so that any forces acting on the model forearm did not affect values measured in the load cell. (iii) There was an approximately 10 mm gap between the hand model and the model forearm that was covered with the wrist part of a surgical glove (hereafter termed the "rubber shield") to make the inside of the model forearm watertight. The magnitude of error in drag or lift forces acting on the hand model measured by the load cell due to the tension acting on the rubber shield and cross-talk error in the load cell was 3 N when the force acting on the hand model was 53 N. (iv) The load cell was covered by a thin pair of plastic containers isolated from each other to avoid splashes. (v) The gap between the plastic containers was covered by a thin plastic sheet. The gap in the upper part of the forearm was also covered by a thin plastic sheet to avoid splashes during measurements. As the plastic sheet was loosely attached, there was no pressure difference amongst the inside of the model forearm and the layers of plastic, and therefore, the layers of plastic did not appreciably disturb forces measured by the load cell.

The isolated hand model was attached vertically in the flume and was immersed in the depth of 0.5 m. Thus, the hand part was completely under water in the testing while the surface wave occurred on the upper part of the model's forearm. The measurements of drag and lift forces acting on the hand were conducted for 5 s sampling at 100 Hz when the flow speed in the flume was set at 1.5 m/s, and α was set from 30° to 150° in 20° increments. Throughout the measurements, the inside of the model forearm (the hollow cylinder) was checked to ensure there was no leakage into the forearm model.

The values of C_d and C_l were calculated by Eqs. (1) and (2). The values were not influenced by wave drag, because fluid forces acting on the hand placed under the water were measured independently of fluid forces acting on the model forearm experiencing wave drag.

3. Results

The values of C_{d_w} were larger than C_d overall while both the curves were somewhat similar being concave down (Fig. 3). The values of C_{d_w} at $\alpha = 30°$, 90°, 150° were 53%, 46%, and 98% larger than for C_d, respectively. The values and the trend of C_{l_w} were similar to C_l overall (Fig. 4). The magnitudes of C_{l_w} at $\alpha = 30°$ and 90° were 2% and 8% smaller than for C_l, respectively, while C_{l_w} at $\alpha = 150°$ was 12% greater than for C_l.

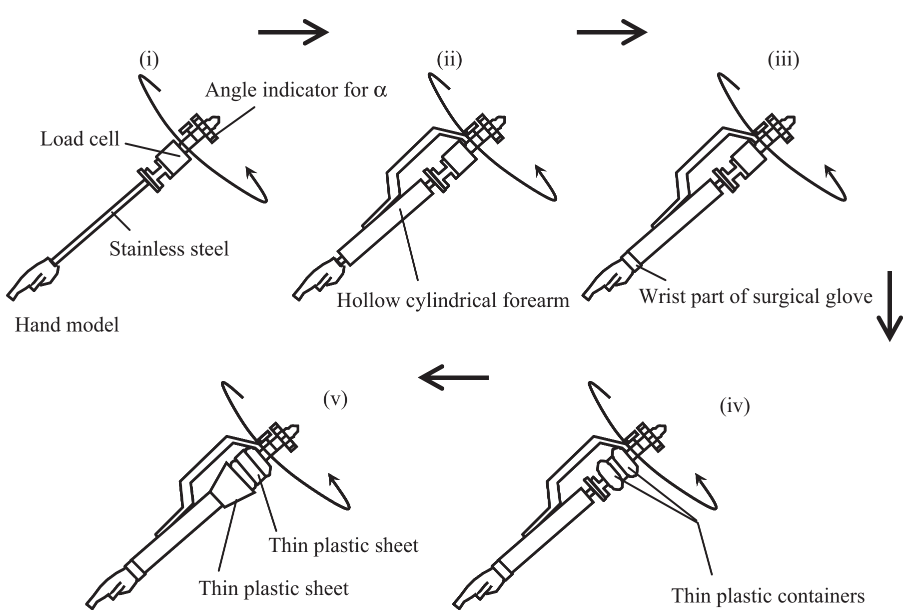

Fig. 2. The process to build the isolated hand model.

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