ACCELERATION EFFECT ON FLUID FORCES ACTING ON THE HAND IN SWIMMING

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This study aimed to quantify and investigate the effect of acceleration on fluid forces acting on a hand model. An accelerating hand in swimming generates large fluid forces in a stroke, although the effect of acceleration on fluid forces on the hand has not been well quantified. An experiment rotating a hand model in a flowing flume was conducted to measure fluid forces on the hand model and pressure on the hand surface. The effect of acceleration on fluid forces acting on the hand was quantified based on a theoretical understanding in fluid mechanics. Accelerated motion induced additional fluid forces on the hand, consistent with the theoretical understanding while decelerated motion induced additional fluid forces, not consistent with the theoretical understanding. Dynamic pressures measured were attributed to the formation of large vortices, inducing the additional fluid forces.

KEYWORDS: Inertia coefficient, deceleration, non-accelerating and accelerating hand

INTRODUCTION:
The hands are an important contributor to propulsion in the front crawl stroke. Forces exerted by the hands have been quantified based on the coefficient of fluid forces known as the quasi-static approach (Schleihau, 1979), and the results have been applied to the technical recommendations for the stroke. However, the accelerating hand in swimming needs to be considered for the quantification of fluid forces acting on the hand (Pai & Hay, 1988). The effect of acceleration on fluid forces acting on the hand in swimming has not yet been well quantified. The aim of the present study was to quantify and investigate the effect of acceleration on fluid forces (H) acting on a hand model. The findings were expected to result in a better understanding of the generation of fluid forces on the hand in swimming.

METHOD:
Experiments were conducted in a flowing flume at a constant speed, so as to measure the pressure on the surface of a hand model and the resultant fluid force acting on the hand model in accelerated and non-accelerated motion (Fig. 1). Five pressure sensors (KYOWA, Tokyo, Japan) were used to measure pressure on the surface of the hand model as shown in Fig. 1. The locations were the side of head of the fifth metacarpal for one sensor (p3) and the head of the third and fourth metacarpal (p1 and p2 on the ventral side and p5 and p4 on the dorsal side) for four sensors. The pressure values were used to deduce the flow conditions around the hand model. The hand model was attached to a load cell (AMTI, Massachusetts, USA) by a stainless bar that was covered by a hollow cylindrical model "forearm". The model forearm was fixed so as to not affect the values measured in the load cell. A thin elastic material made watertight covered the gap between the hand model and the model forearm. Thus, the present study derived only fluid forces acting on the hand model using the equation of motion in the t-direction perpendicular to the model’s longitudinal axis (Ht). The angular position of the model (φ) was measured by a potentiometer. The orientation of the hand model was with the hand surface perpendicular to the model rotation plane. The flow speed relative to the hand model, U, was calculated from the velocity in the flume and the velocity of the hand model. The angle of incidence, β, was defined as the angle between the model’s longitudinal axis and the flow direction relative to the hand. β was defined as 0° when the direction of flows relative to the hand model was parallel to the longitudinal axis and toward the rotation axis and was 90° when the relative flow direction was perpendicular to the longitudinal axis and toward the palm side. The flow
speed in the flume and the amount of driving masses were changed to produce various
different values of U and acceleration in the t-direction, a, for the accelerating hand testing.

Fluid forces acting on the hand model in accelerated motion were expressed by the following
equation (Daniel, 1984; Morison, O’Brien, Johnson, & Schaf, 1950):

\[ H_t = \rho V C_i a + 0.5 \rho A C_d U^2 \]  

where \( \rho \) is the density of fluid, \( V \) is the hand volume, \( C_i \) is the inertia coefficient, \( A \) is the
hand area, and \( C_d \) is the coefficient of fluid force in the t-direction.
The values of \( C_i \) and \( C_d \) were determined from all trials of differing U and a for each \( \beta \) from
10° to 130° in 10° increments. \( H_t \) was predicted by data in the non-accelerating hand (\( H_t^0 \)),
and the difference between \( H_t \) and \( H_t^0 \) was calculated (\( H_t - H_t^0 \)).

Knowing hydrostatic pressures from the depth of the hand model, hydrodynamic pressures
were derived by subtracting the hydrostatic pressures from the pressures measured by the
pressure sensors. Using the dynamic pressure in the non-accelerating hand, the dynamic
pressure for the accelerating hand model was predicted (\( p^0 \)).

RESULTS:
The value of \( C_i \) increased until \( \beta = 60^\circ \) (4.0) in the early phase of model rotation and then
decreased until \( \beta = 100^\circ \) (-3.3) in the late phase while the average of a changed from -4
m/s² to 13 m/s² (Figs. 2 and 3). The value of \( H_t - H_t^0 \) increased as a increased when \( C_i \) was
maximum (\( \beta = 60^\circ \)), and the value of \( H_t - H_t^0 \) increased as a decreased when \( C_i \) was
minimum (\( \beta = 100^\circ \)) as shown in Fig. 4 and Fig. 5, respectively. The maximum \( H_t - H_t^0 \) at \( \beta = 60^\circ \) was 26 N (\( H_t = 33 \) N and \( H_t^0 = 7 \) N), and the maximum \( H_t - H_t^0 \) at \( \beta = 100^\circ \) was 49 N (\( H_t = 107 \) N and \( H_t^0 = 58 \) N).

DISCUSSION:
\( H_t - H_t^0 \) increased as a increased at \( \beta = 60^\circ \) (Fig. 4). \( H_t \) was approximately 4 times greater
than \( H_t^0 \). The value of a was large and positive when \( \beta \) became maximum at 60°. The results are consistent with the theoretical understanding that fluid forces acting on an object
increase due to the acceleration reaction for the positive accelerated motion (Daniel, 1984).
As shown in Fig. 5, \( H_t - H_t^0 \) increased as a decreased. \( H_t \) was approximately 2 times greater
than \( H_t^0 \) while the magnitude was larger than that for \( \beta = 60^\circ \). The value of a was small or
negative when \( \beta \) became minimum at 100°. The results are not consistent with the
theoretical understanding because \( H_t \) increased while a decreased.

In the present study, \( H_t \) depended on the pressure difference between the dorsal and ventral
sides of the hand model since U was relatively fast (high Reynolds number). The pressure
distribution around the hand model should be influenced by flow conditions around the model. Thus, the pressure values measured were used to deduce flow conditions around the hand model (Figs. 6 and 7). At $\beta = 60^\circ$ as shown in Fig. 6, the largely different value between $p_4$ and $p_4^0$ and the decrease in pressure from $p_3$ to $p_5$ indicates that large attached vortices involving high intensity and velocity flow might be generated inducing additional $H_t$ as seen in Figs. 4. The impulsive-started motion induces large attached vortices behind a blunt object and additional fluid forces on the object (Sarpkaya & Isaacson, 1981). At $\beta = 100^\circ$ as shown in Fig. 7, the values of $p_4$ and $p_5$ were much lower than those of $p_4^0$ and $p_5^0$. The larger pressure difference in the accelerating hand model than for the non-accelerating hand model was due to the large magnitude of negative pressure on the dorsal side of the hand model. The negative pressure may be due to the generation of large vortices since, although the study of Maresca, Favier, & Rebont (1979) used an aerofoil set at 20° of angle of attack, the previous study showed that vortices behind the aerofoil disintegrated in decelerated motion, and fluid forces on the aerofoil and the magnitude of negative pressure on the dorsal side of the aerofoil became much larger than for the steady case.

Figure 2: The value of $a_t$ for various $\beta$

Figure 3: The value of $C_{i1}$ for various $\beta$

Figure 4: The value of $H_t - H_t^0$ as a function of $a_t$ at $\beta = 60^\circ$

Figure 5: The value of $H_t - H_t^0$ as a function of $a_t$ at $\beta = 100^\circ$

Figure 6: Pressure at the various sensors at $\beta = 60^\circ$

Figure 7: Pressure at the various sensors at $\beta = 100^\circ$
CONCLUSION:
Accelerated motion induces additional fluid forces on the hand in swimming up to 4 times larger than non-accelerated motion. The theory for decelerated hand motion needs to be developed for understanding the mechanism of additional fluid forces on the hand.

References: