CFD ANALYSIS OF A SWIMMER'S ARM AND HAND, ACCELERATION AND DECELERATION

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The numerical technique of computational fluid dynamics (CFD) has been used to determine the effect of arm and hand acceleration and deceleration on the propulsive forces generated by swimmers. Relationships developed to predict hand and arm forces as a function of both velocity and acceleration show these forces can be significantly different from those calculated using the quasi-steady approach. Simple equations that provide a correction factor to forces calculated using the quasi-steady approach are provided. The analyses showed that drag and axial forces (along length of the arm) were affected more by unsteady flow than were the lift forces. Also, arm forces were affected more than were hand forces. And finally, maximum propulsion was obtained from the hand when it faced directly backwards towards the feet, even though the stroke itself may be moving diagonally.

KEY **WORDS:** acceleration, computational fluid dynamics, unsteady flow, drag, lift, propulsion

INTRODUCTION: Initial investigations into swimming propulsion were strictly experimental. Models of hands and arms were flow tested in steady flow conditions in wind tunnels (Wood, 1977), flumes (Schleihauf, 1979), and tow tanks (Berger, de Groot, and Hollander, 1995). Unsteady conditions were evaluated by Thayer (1990) and Sanders (1999), who showed experimentally that acceleration and deceleration can significantly affect hand force coefficients. These researchers also revealed some of the difficulties involved in conducting such studies experimentally. They had to choose between unwanted wave and ventilation drag or inaccurate interference drag. An alternative approach to analyze propulsion is to utilize a numerical technique called computational fluid dynamics (CFD). In addition to avoiding wave, ventilation, and interference drag, CFD has the added advantage of being able to show detailed characteristics of fluid flow.

CFD was first applied to swimming by Bixler and Schloder (1996). They found that a hand-size object accelerating through water could have a drag coefficient more than 40% greater than the coefficient calculated using quasi-steady methods. This was followed by a CFD steady-state analysis of an actual hand and forearm (Bixler, 1999), where the force coefficients calculated using CFD techniques compared favorably with coefficients obtained experimentally by Wood (1977), Schleihauf (1979), and Berger et. al. (1995). The present research extends beyond steady flow into unsteady flow, and analyzes the propulsive forces generated by an accelerating and decelerating hand and arm.

METHODS: The CFD model of a swimmer's hand and arm used previously to model steady flow (Bixler, 1999) was also utilized to model the unsteady flow of the present study. Although all geometry, coordinate systems, and fluid properties remained the same, the solution technique was modified to obtain transient solutions. In a transient analysis, a model is analyzed for an initial velocity, then time and velocity are incremented by a small amount corresponding to the acceleration or deceleration desired, and the model is analyzed again. These time steps are repeated until the desired final time and velocity are reached. Typical transient analyses in this study required between 100 and 125 steps.

The independent variables were initial velocity, final velocity, acceleration, and angle of attack. Initial and final velocities and stroke time were chosen to be representative of what is seen during a swimming stroke. Acceleration was held constant for all cases. Table 1 shows the combinations of variables that were analyzed. Each of these combinations was analyzed at angles of attack of 60, 90, and 135 degrees with a zero degree sweepback angle. As determined by the steady flow analysis of Bixler (1999), these three angles provide different combinations of lift and drag forces for evaluation.

Table **1** Combinations **of** Variables Analyzed

Initial Velocity (mls)	Final Velocity (rnls)	At (s)	Acceleration **(m/s$^{2)}$**
0.5	2.0	0.25	6
		0.50	3
	1.5	0.25	4
		0.50	2
	0.0	0.25	–2
		0.50	–1
1.5	2.5	0.10	10
		0.25	4
	3.5	0.10	20
		0.25	8
	0.5	0.10	–10
		0.25	–4

Each transient was initiated with the steady-state solution for the initial velocity of the transient. After each analysis, drag, 2Dlift, and axial force components were calculated at each time step by integration of pressures on the hand/arm surfaces, and then force time-history plots were created to show the change in force over time. All force components are defined as in the original steady-state analyses (Bixler, 1999).

RESULTS: Typical force time histories are shown in Figure 1 for an acceleration of 4 m/s^2 at an angle of attack of 60 degrees. Notable trends from this and other cases show that:

1. Axial forces are significant.
2. Upon initiation of acceleration, there is a sudden increase in force.
3. Acceleration and deceleration have stronger effects on drag than on lift.
4. Deceleration can produce a negative force (not shown) even while the velocity of the arm/hand is still positive.
5. Arm lift is essentially zero (not shown), as it was in the steady-state analyses.
6. Analysis of hand-only and arm-only drag (not shown) reveal that acceleration increases arm drag more than it does hand drag.
7. Maximum hand propulsive force is achieved when the palm of the hand is facing directly towards the feet (even though the stroke itself may be moving diagonally).

DISCUSSION: A well-known parameter called the acceleration number (6) was shown by Iversen and Balent (1951) to correlate very well with unsteady drag resistance. The acceleration number is defined as $6 = aL/V^2$, where a is acceleration, L is a characteristic length (max arm diameter), and V is an average velocity during a stroke segment.
The acceleration number was correlated to $F/\rho a\forall$, where F was the time-weighted average force during a stroke segment, obtained by integrating the force time history with respect to time, and then dividing by the total stroke time. This was nondimensionalized by dividing by ρ (water density), a (acceleration), and $\forall$ (volume of the object for which forces are being calculated). Figure 2 provides an example of how clearly these nondimensional parameters provide very clean relationships between velocity, acceleration, and force.
It was desired to establish whether simple relationships existed between forces from quasi-steady calculations and forces from the unsteady analysis. Indeed, such relationships were found, and one of them is shown in Figure 3.

Case	Force	Vel_{init}	Part	Angle	Ratio of Unsteady force/Quasi-steady force
Accel	Drag	all	Hand	all	$= 1.2\ aL/V^2 + 1.0$
Accel	Drag	all	Arm	all	$= 2.4\ aL/V^2 + 1.0$
Decel	Drag	1.5	Hand	all	$= 1.2\ aL/V^2 + 1.0$
Decel	Drag	1.5	Arm	all	$= 2.5\ aL/V^2 + 1.0$
Accel	Lift	all	Hand	60	$= 0.7\ aL/V^2 + 1.0$
Accel	Lift	all	Hand	135	$= 0.2\ aL/V^2 + 1.0$
Decel	Lift	all	Hand	60	$= .35\ aIN^2 + 1.0$
Decel	Lift	all	Hand	135	$= .25\ aL/V^2 + 1.0$

These relationships reveal that acceleration and deceleration affect the arm drag twice as much as they do the hand drag. They also affect drag more than they do lift (Riewald and Bixler, 2001).

Two researchers have experimentally evaluated unsteady flow. Thayer (1990) examined unsteady flow caused by rotation of the hand and arm, making her results not directly comparable to those of the present research. However, Sanders (1999) examined unidirectional unsteady flow similar to that studied herein. While the present study utilized the acceleration number concept, Sanders developed acceleration coefficients, which were generally only about 6% of the velocity coefficients, indicating the unsteady flow had less of an effect than it did in the present study. Several facts could account for the differences:

1. Acceleration constants were not dimensionless, and it was not established whether the accelerations were independent of hand speed, which was always below .6 mlsec.
2. The accelerations were not necessarily constant, and the effect of accelerations that were not in the direction of motion of the hand were not incorporated in the model.
3. Inaccurate interference drag between the support rod and the hand model.
4. Support rod and hand flexibility could also account for lower coefficients.

CONCLUSIONS: This research has brought us one step closer to the ultimate goal: "designing" complete arm strokes. It will also provide coaches with the following information:

1. Swimmers should strive to keep their hands and arms accelerating as much as possible. Even a slight deceleration can result in a significant reduction of the propelling force.
2. The hand should be in a position to maximize drag during the acceleration part of a stroke.
3. The arm plays a larger role in propulsion than previously thought, because acceleration can increase arm drag force twice as much as it increases the hand drag force.
4. Maximum hand propulsion is obtained by positioning the palm of the hand so that it is facing directly towards the feet, even though the stroke itself may be moving diagonally.

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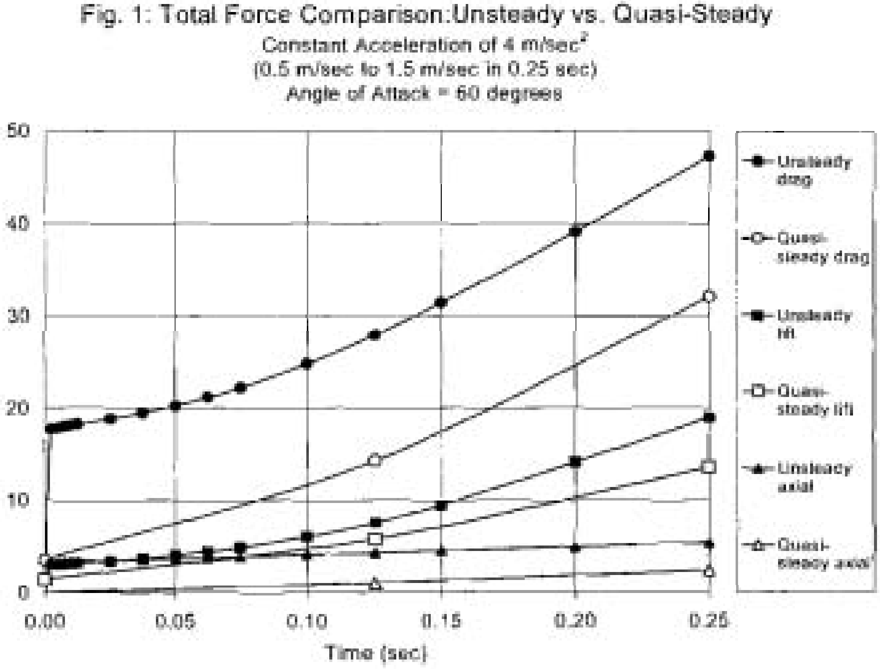

Figure 1 – Total force comparison: Unsteady vs, Quasi Steady

Fig 2: Hand Drag Force Relationships to Velocity and Acceleration

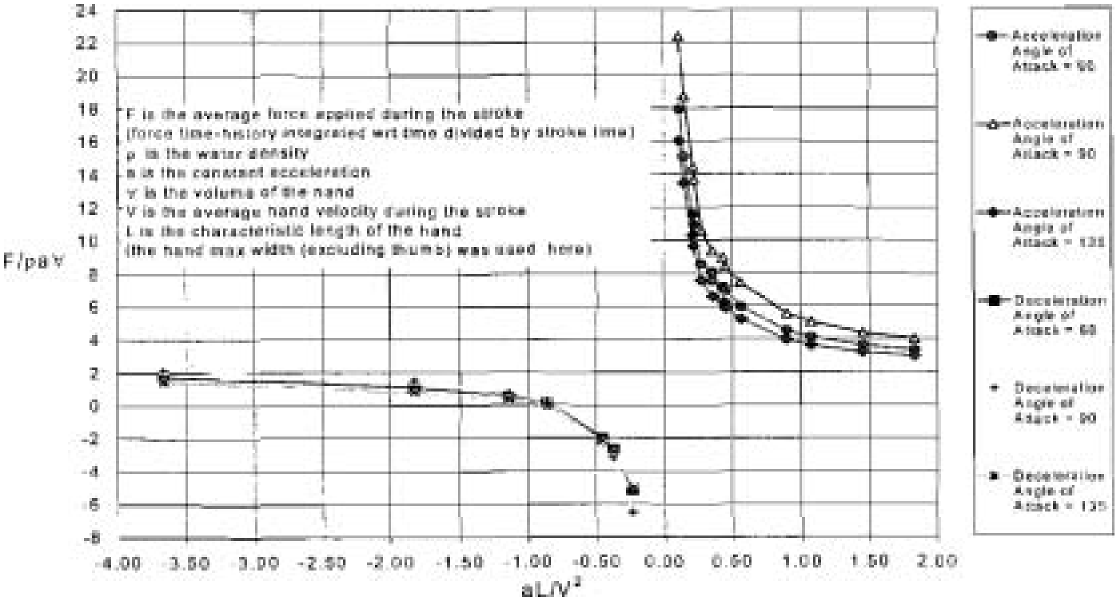

Figure 2 – Hand drag force relationships to velocity and acceleration

Fig 3: **Ratio of Arm** Unsteady/Quasi-Steady **Drag vs. Accel number**

All Angles of Attack and both Initial Velocities, Positive Acceleration Only

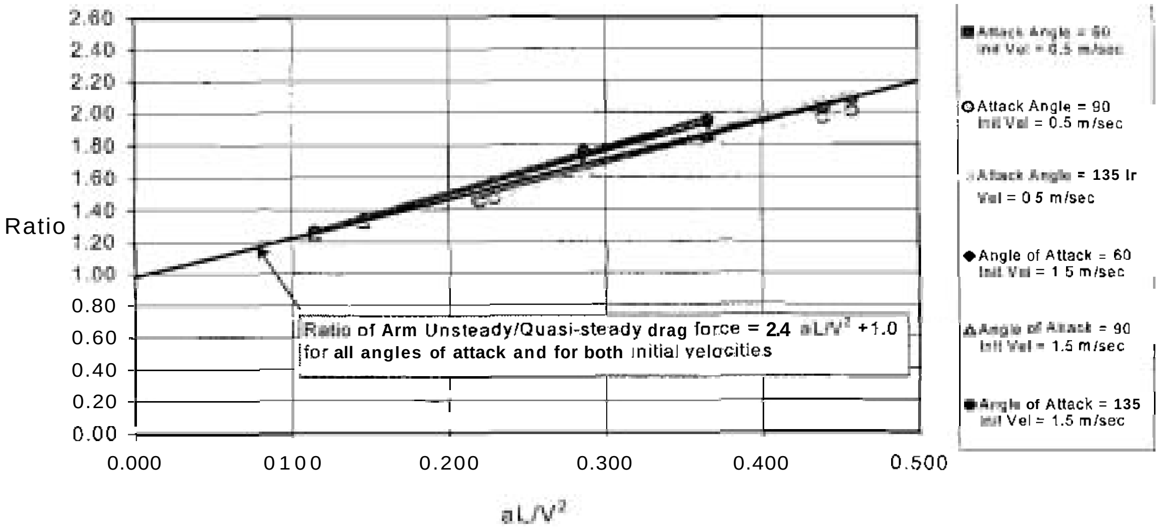

Figure 3 – Ratio of arm unsteady/quasi-steady drag vs acceleration number: All angles of attack and both initial velocities, positive acceleration only.