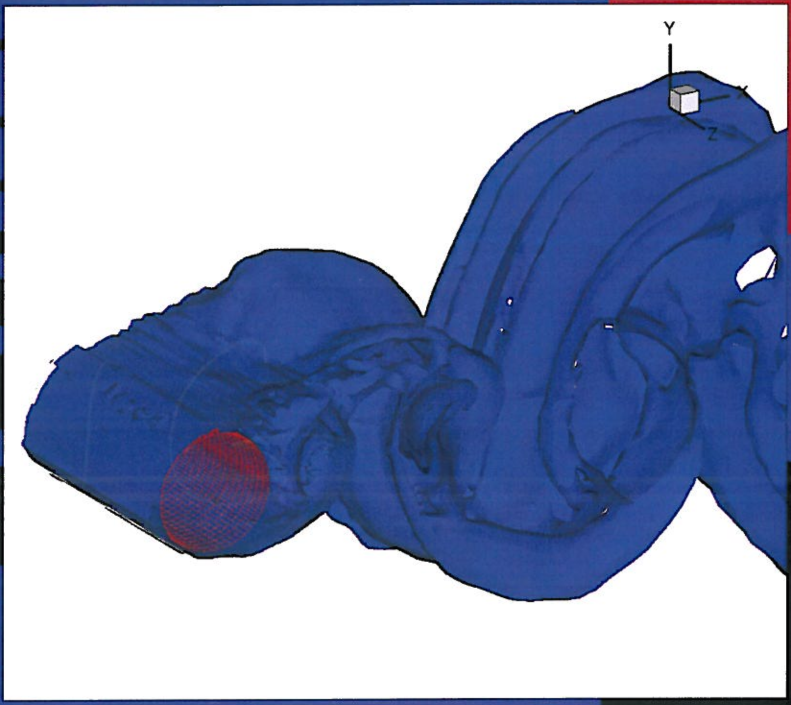

Conference

TOPICAL PROBLEMS OF FLUID MECHANICS 2013

Institute of Thermomechanics AS CR
Dolejškova 5, CZ-182 00 Prague

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THE ROLE OF VORTICITY IN MAXIMAL SWIMMING PROPULSION

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Abstract

Experimental and theoretical results on the propulsion of swimmers are presented with an emphasis on the specific characteristics of the wakes produced by the swimmers in the water. We introduce the subject revising some of the previous work on the fruitless controversy between Drag and Lift components of the forces induced by swimmers hands. After presenting some experimental results on Underwater Oscillatory Swimming we discuss in detail the complex nature of the swimmers body, feet and hand wakes and show the role of vortices. Several basic recommendations may be deduced comparing animal and human swimming. One is the need to reduce Strouhal numbers to increase propulsion, the other one is to generate wakes that maximize momentum and minimize energy, this is discussed in terms of the fluid topological properties of basic vortical flow configurations.

Keywords: swimming, propulsion, vortices

1 Introduction

Studies in the animal world and in sport biomechanics show often how vortices are generated during human swimming as well as in the flight of birds and the propulsion of fish or dolphins. [1-6], they show in nature that there is a Strouhal number of 0.2 associated to usual propulsion, which seems to be associated to maximum efficiency. In detailed observations of propulsive wakes, other observations may be studied considering the momentum, energy and vorticity balances created during propulsion within a fluid. We recorded propulsive force during tethered swimming and also used bubbles to trace the water flow [7-9]. Vorticity in wakes was seen to be dominant in the best swimmers, whose circulation produced by both hands and feet (eddies or vortex structures) were more regular. When non-steady motions occur Zhukovsky's condition is not met and unbound vortices are shed at the tips of the hands and feet in a turbulent 3D fashion forming a complex wake. Film recordings of hand swimming motions of high level competitors, Counsilman [5] in 1971 showed clearly that sideways arm movements were dominant in human swimming and that lift contributed as a thrust mechanism. This was measured in a quantitative way by Redondo et al. [7-9] using piezoceramic sensors to evaluate both drag and lift in competitive swimmers. In observations of swimmers wakes as well as in theoretical arguments of jet propulsion [10] it has been shown that efficient propulsion is obtained by pushing a large mass of water a short distance rather than imparting momentum on a small volume of water, which is accelerated backwards with an obvious loss of efficiency. For a single 3D axisimetric vortex dipole structure it is interesting to find the geometry of the propulsive vortex with most backward momentum and minimum energy. These basic wake configurations may be measured and extended to different types of complex and intermittent turbulent wakes produced by different parts of the human body [11-16]. We will first discuss the basic measurements and some visualizations and finaly present some recomendations for maximal propulsion.

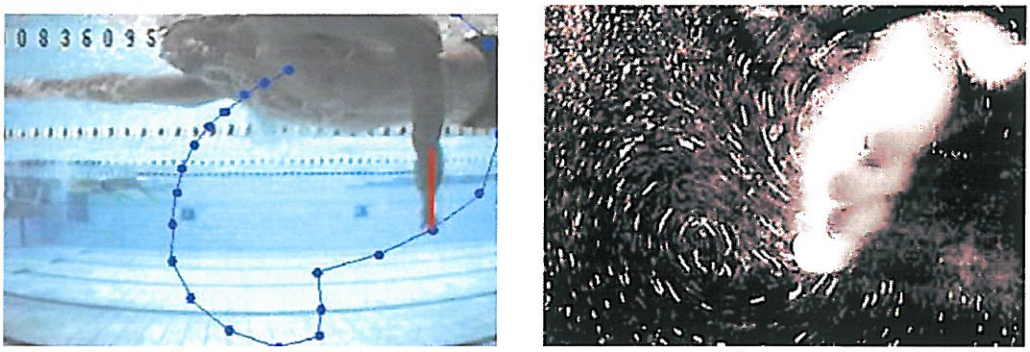
2 Wake flow description

Considering the wake produced by a hand or a foot of a swimmer thrusting water backwards so it can be propelled forward due to a complex combination of unsteady Lift and Drag, it should be possible to measure not only the detailled trayectory of the body parts in the water, but also the motions of the water, this may be observed in figure 1 for the hand of a swimmer and in figure 2 air bubbles injected as swimmers propell themselves show how vortical structures are common. In order to describe a wake, we can apply Navier-Stokes equation, applying vorticity as $\omega = \nabla x u$, we obtain the evolution of vorticity:

$$\frac{D\omega}{Dt} = \omega\nabla u + \nu\nabla^2\omega + \nabla p \wedge \nabla\left(\frac{I}{\rho}\right) \qquad (1)$$

If density and viscosity are ρ and $\nu = \mu / \rho_0$. The last term, baroclinic production of vorticity will only be effective if the fluid is non homogeneous, and when $\nabla p \, \mathrm{y} \, \nabla \rho$ are not parallel. This term could be important when local temperature gradients are important and most of the times can be ignored, thus the basic production of vorticity is the interactions between velocity gradients and vorticity. Viscosity only acts as a sink of vorticity. In a fully turbulent flow velocity and vorticity correlations are also important when evaluating the balances of momentum, energy and vorticity. Note that even measuring one component of vorticity (perpendicular to a 2D PIV plane) as seen in figure 3, the real flow is three dimensional as seen by [12] in numerical simulations of underwater undulatory swimming UUS. Vorticity production in a plane may also be evaluated as a Circulation

$$\tau = \int u \cdot dl = \iint \omega \cdot dA, \qquad (2)$$



a) b)

Figure 1: Trajectory of the hand and of its wake in 2D during swimming [1,2]

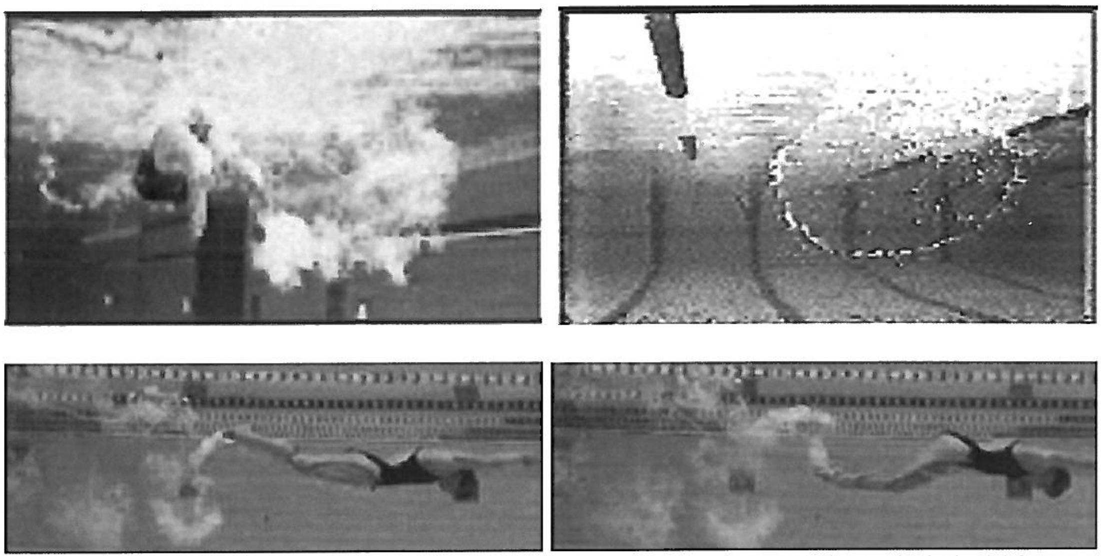


Figure 2: Example of UUS visualization of the wake by injected air bubbles, The vortex lines are indicated by the trapping of bubbles

2.1 Laboratory experiments

A 1 m^3 aquarium was used in the laboratory with small pliolite reflective particles were placed in the water with density similar to the water. A .2 W solid state laser projected a parallel plane of light produced by a cylindrical lens. The plane of Laser light allowed to observe easily the position of the pliolite previously sived 100 μm particles. A video camera was placed perpendicular to the aquarium. The shutter speed was low to see easily the path of the particles. Attack angles between 40° - 70° were examined showing a direct relationship between the size of the vortex and the angle of attack. Trials and calibration is necessary to capture the movement of an oscillating plate to show the vorticity structure by means of PIV using DigImage program as shown in figures 3 and 4. In swimming pool experiments, the coherence of the vortex rotation after kicks or the generation vortices with higher persistence during the hand pull seem related to higher propulsion. This effect was analyzed by Linden and Turner [10] for a single propulsive vortex ring [2] but an statistical comparison of the momentum and vorticity in complex wakes, like in the measurements of lift and drag [9,10] seems important to understand the role of coherent vorticity in propulsive wake. The importance of intermittency and coherence in propulsion may be also analyzed using ESS and measuring intermittency such as in other complex flows [13,14]. We can apply here a model of a single spherical vortex ring such as a Hill vortex to an UUS single kick considering both up and down motions from a centerline position, then considering that the chord of the fin or feet is c, the motion is twice the amplitude $2h$ and L is the distance from the knee to the toe (or fin side) then the momentum can be calculated in terms of the integrated velocity of the backwards water

$$V = \int u(z,y)\cdot dA = \iint u(z,y)dzdy, \qquad (3)$$

The momentum is then $M = \rho LhcV$

The Kinetic energy is $KE = \Sigma \tfrac{1}{2} \rho LhcV^2$ (4)

In a similar way as for an axisimetric vortex at speed U

$$P = \frac{8}{3}\rho a^3 U \qquad \tau = \frac{4}{\pi} aU \qquad KE = \frac{4}{3}\rho a^3 U^2$$

Here the Strouhal number, being *T* the time of a kick, can be defined as

$$St = \frac{1}{A}\int St(z, y)dA = \frac{h}{VT}, \tag{5}$$

And considering that *L/h = 3.5* provides the maximum momentum with minimum energy [10] and *h/L* provides the most efficient Strouhal number of about 0.3, although for human swimmers it is closer to 0.6, then an integrated vorticity of *2V/h* seems to agree with the best swimmers analyzed [15-17].

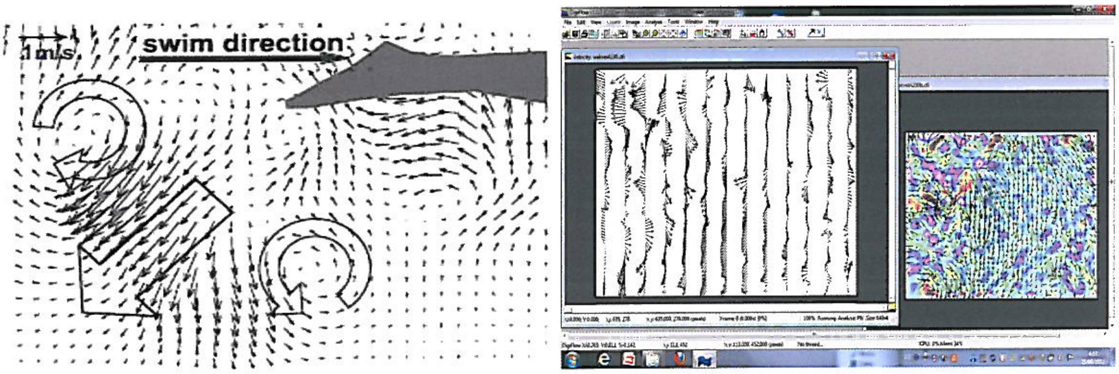


Figure 3: Flow patterns in butterfly kick and in a laboratory wake

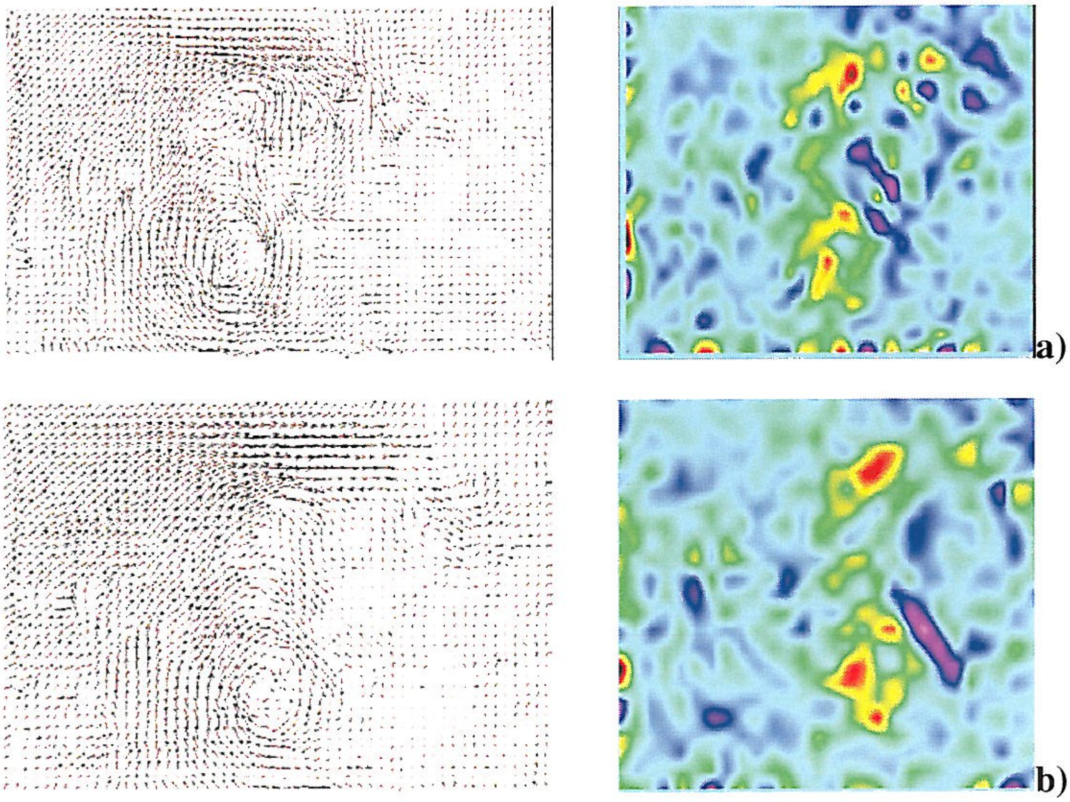


Figure 4: PIV 2D visualization of a UUS kick

The flow behaviour observed during the different experiments agrees with the general theories of flow dynamics. The several propulsive movements analysed (arm pulls and leg kicks) generated large or starting vortices during linear movements that show 3D patterns and are non steady. When the hands or feet accelerated or changed the direction suddenly the vortex is detached into a vortex line. Here water rotation is produced automatically in a correct propulsion and the faster the swimmer the clearer the production of long lasting vortex lines. The swimmers do not appreciate the differences between lift or drag forces, as they are just the components of a strongly unsteady effect the swimmers feel only the resultant force as well as the added mass effects. This means that some swimmers can apply their propulsive force better controlling the direction of the resultant force. In swimming a full stroke, it should be possible to sincronize the pull and the kick in order to benefit from some of the resultant forward momentum resulting from a large vertical pattern. Periodic flows such as that seen in figure 5 produced by an oscillating airfoil [17] reinforce the need for correct timing in pull and kick.

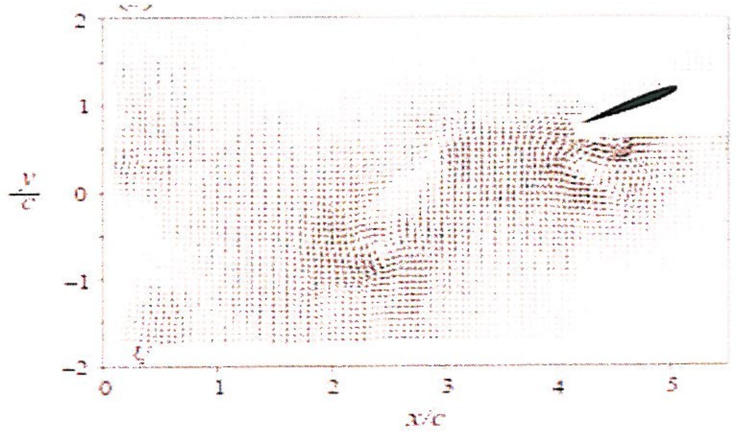


Figure 5: 2D DPIV velocity data for an oscillating foil at its minimum heave position, and Stanton number $St = 0{:}33$, Chord to amplitude ratio one $h/c = 1$, *max angle* = 52,7, $\phi = 30$. From [17]

2.2 Observations of vortex lines

It is also common to observe in some of the best swimmers, of world class the generation of double vortex lines as is shown in figure 6a) for M. Phelps swimming butterfly. The mechanism seems to be a fast oscillation of the hands as they enter the water, these double vortex lines, which are difficult to see without entrained air bubbles are also more persistent and they probably also are more efficient as sources of backward propulsion. The Energy and momentum of a single vortex line with a winding factor of one is not as large as one with a more complex topological pattern [18-20] as shown in figure 6b). More observations of real wake patterns should be analyzed in real maximal swimming conditions, but some conclusions may be stated.

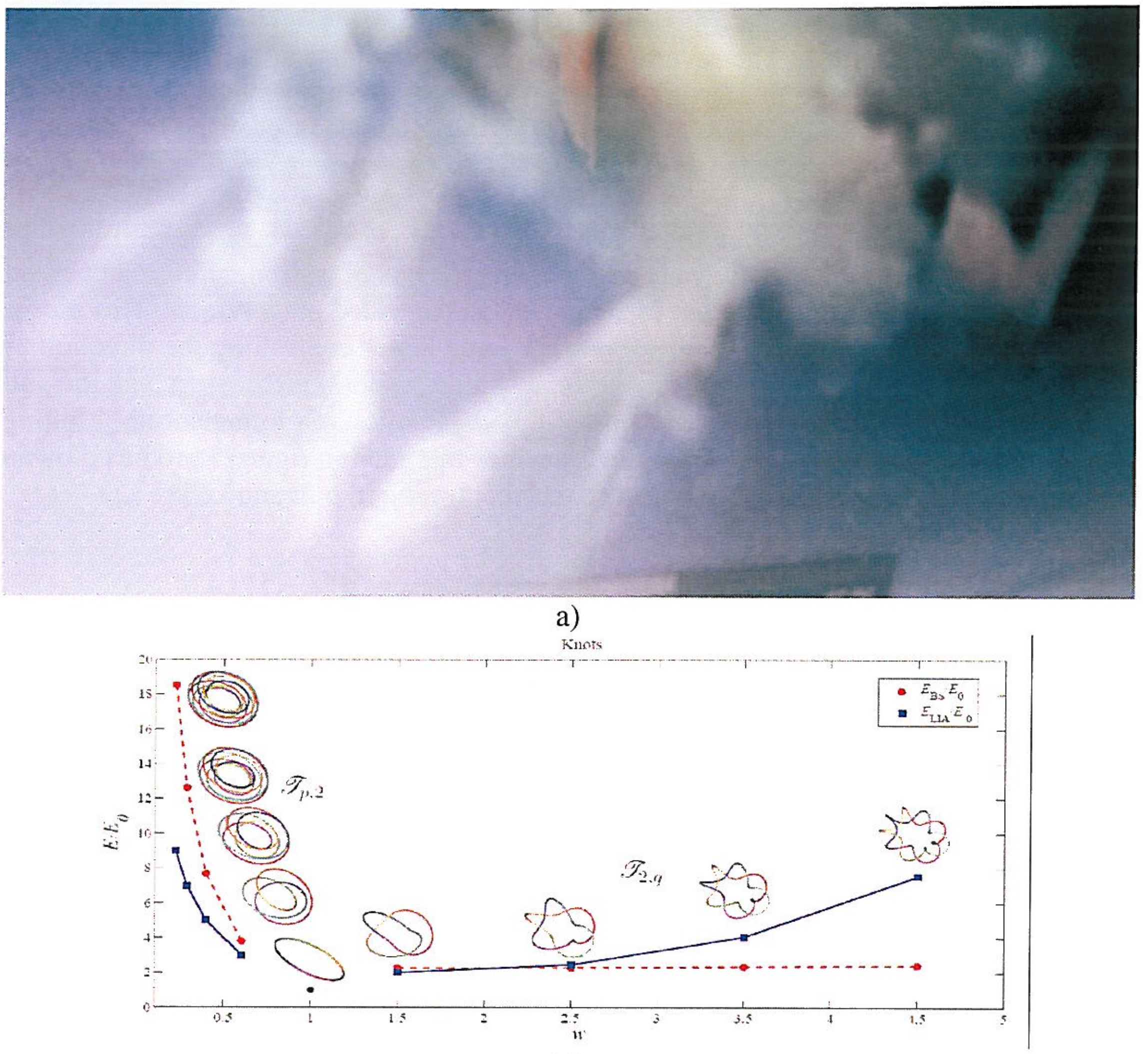

a)
b)

Figure 6: a) 3D side visualization of double vortex lines on the hand wakes of butterfly stroke (M. Phelps).b) Energy required for vortex lines of different winding number. From [20]

3 Conclusions and recommendations

Some situations observed in our experiments such as keeping the vortex rotating stationary after the kick and to develop larger vortices during the hand pull seem related to higher propulsion. Incorrect propulsive movements observed in less efficient swimmers are to propel backwards faster the vortex lines generated or to generate an array of weak or small vortices. Vortex evolution can be studied in the context of the Euler equations by direct numerical integration of the Biot-Savart law and the velocity, helicity and kinetic energy of different vortex knots and unknots can be compared and parameterized by the winding number w given by the ratio of the number of meridian wraps to longitudinal wraps [20] find that for $w < 1$ vortex knots and toroidal coils move faster and carry more energy than a reference vortex ring of same size and circulation, whereas for $w>1$ knots and poloidal coils have approximately same speed and energy. This would explain why double vortex lines as well as a coherent pattern would provide a propulsive advantage.

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