TEACHING HYDRODYNAMIC CONCEPTS RELATED TO SWIMMING PROPULSION USING FLOW VISUALIZATION TECHNIQUES IN THE POOL

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The application of concepts of unsteady fluid dynamics to competitive swimming may open a new way of understanding swimming propulsion. Qualitative methods of flow visualization are proposed to observe how the wakes created during swimming propulsion has a particular behavior related to propulsive movements: 1) flow visualization using small particles; 2) flow visualization injecting bubbles and; 3) flow visualization using a bubble wall. The complex task of teaching the hydrodynamics of a swimmer's propulsion to undergraduate students of Physical Education can be simplified if the students have the opportunity to see how the water is actively moving when the body is propelled through the water.

KEY WORDS: propulsion, vortex, circulation, flow visualization, teaching methods

INTRODUCTION: Teaching fluid mechanics applied to undergraduate students of Physical Education who are intending to specialize in swimming coaching has traditionally been a difficult task for the sport biomechanics teacher. The theories are complex and difficult to understand because they are based on indirect methods of calculating the propulsive force and is difficult to relate to swimmer movements. Recently marine biologists have developed methods to visualize the flow around animals and their propulsive segments interpreting of the wake behind the biofoil and analysis of vortices generated to understand why some fish movements are so efficient in comparison to the propulsive movements made by the human being. The objectives of the class activities proposed in this paper are: a) to show how it is possible to see the water movements related to the propulsive movements with relatively simple visualization systems; b) to relate the water behavior around the propulsive segment to the different positions and movements that segment performs and; c) to differentiate the wakes and vortices generated by the different body segments.

A BRIEF HISTORY OF SWIMMING PROPULSION THEORIES: Butovich and Chudovskiy (1968) and Counsilman (1971) were the first authors to try to apply the knowledge of hydrodynamics to develop a theory about swimming propulsion. They examined the different roles played by the two components of propulsion: lift and drag. Counsilman (1971) based the explanation of the lift component on Bernoulli´s Principle and compared the swimmer's hand with a boat propeller. Later, Schleihauf (1974); Schleihauf (1979); Schleihauf, Gray, and DeRose (1983) studied the problem in applying the equations of lift and drag to calculate the forces associated with the hand's movements. Further analysis and experimental studies about this matter were recently developed by Berger, Groot and Hollander (1995); Payton and Bartlett (1995). But in this approach the analysis was done using the hand path through the water, not observing the kind of perturbations that the hand is producing in the water and how the energy transfer is achieved. Cecil Colwin (1985) is considered the first author to apply in swimming biomechanics the theories more broadly accepted by the hydrodynamic experts. These theories explain the relationship between propellers or *biofoils* and the fluid *circulation* (Colwin, 1985a; Colwin, 1985b). This author showed bubbles paths generated during human swimming movements. Some bubbles followed a path similar to the pulling path and others moved or rotated showing vortices. Some basic hydrodynamic terms were then added to the swimming theory knowledge: starting vortex, bound vortex, tip vortex and so on. A global theory that includes drag and lift coefficients, flow circulation, starting and bound vortices, Bernoulli´s and Kutta-Zhukovsky's principles, Magnus' effect, steady and unsteady flows, has also been proposed (Arellano, 1999). As Colwin (1999) has said "instead of belaboring the lift versus drag argument, we need to move on and learn more about the way the water reacts when we swim". This suggests that the application of unsteady fluid dynamics to competitive swimming may rejuvenate the debate on the nature of thrust forces (Demont, 1999). Recently marine biologists have developed technology and theories on aquatic movements (Dickinson (1996), Stamhuis and Videler (1995) Videler, Muller and Stamhuis (1999)). When a fish undulates and propels itself with its tail fin, it produces a water displacement that can be observed: wake vortices. Every vortex generated after each stroke has a different rotation (clockwise or anti-clockwise), producing a jet of water undulating between vortices that flows opposite to the swimming direction (Videler et al., 1999). Simple systems of flow visualization have been used during the last two decades by swimming researchers: Colwin (1985a) observed the water movements of air bubbles captured during swimming. Hay and Thayer (1989) used the tuft method to observe how the water particles are moving close to the swimmer's skin. Persyn and Colman (1997) used injected colored dye to study the vortices generated during undulatory underwater swimming. Arellano & Redondo (1998) obtained images of the vortices generated by the hand using reflective small particles. Arellano (1999) used injected bubbles and a bubbles wall. Toussaint (2000) observed the flow around the arms during swimming propulsion using long tufts. Bixler and Schloder (1996) used computer simulation software and predicted the vortex generation during swimming propulsion.

Figure 1 - Vortices generated during a short hand movement.

METHODS: Flow visualization using small particles: A small aquarium was utilized to develop the experiment. Small reflective particles with a density similar to the water were placed in the tank. A big lamp projected light inside the aquarium. The light permitted us to observe easily the position of the water particles (see Figure 1). The video-recorded images (50 Hz, 1/1000 shutter) were analyzed to find how the vortices change when the angle of attack of the hand, the hand velocity or the use of hand-paddles modify the initial situation of the hand movement. The use of a flow analysis hardware-software combination that enhances the particles' movements permitted us to understand the magnitudes of the vortices' movements.

Flow visualization injecting bubbles: A plastic tube of 0.5 cm diameter was connected from an air compressor to the body of the swimmer. A video camera was placed underwater perpendicular to the plane of movement of the swimmer (50 Hz, 1/250 shutter). The air compressor injected air through the tube and a bubble trace of the big toe trajectory was easily observed during underwater kicking. This trace was maintained for approximately one second. When the feet started to flutter kick (undulatory underwater movements) or breaststroke kick, the bubble trace followed the big toe in a laminar path in some phases. In other phases, the bubbles started rotating and kept rotating stationary in the space where they were created. Big vortices were created at the end of vertical downward movements of the feet in the kicking movement of both strokes (see Figure 2). The rotation of the vortices was similar to that cited by researchers studying fish tail propulsion. The swimmers made a non-symmetrical propulsive movement with their legs, producing a vortex at the end of the downward kick, and in some cases a second small vortex after the upward kick. During underwater breaststroke kicking another camera was utilized to view from the back of the kick. The breaststroke kick showed a different vortex rotation changing continuously along the vortex axis of rotation. This system was used as well to video-record small sculling movements made by the hands.

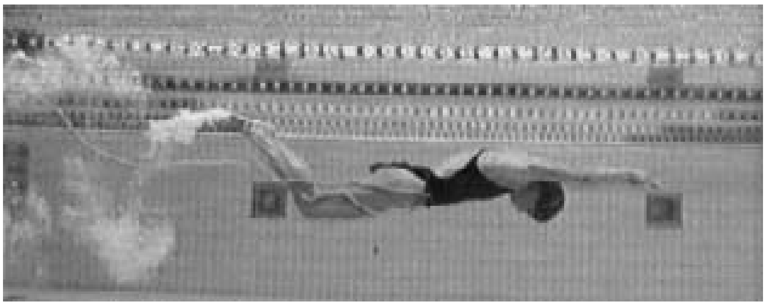

Figure 2 - Vortices generated during underwater undulatory swimming.

Flow visualization using a bubble wall: A plastic tube, 2 cm diameter, two meters in length and with a line of holes of 2 mm diameter every 5 cm, was connected to an air compressor. The tube was placed in a swimming pool 1.5 m deep, parallel to the water surface and swimming pool wall. The camera was located underwater and perpendicular to the bubble wall. When the air bubbled upwards, parallel vertical lines of bubbles (bubble wall) were created. The subject, located vertically or horizontally in front of the underwater window, started to make different propulsive movements. When his hand or feet crossed the bubble wall, it was possible to see whether the water was moving around the propulsive element. Also the swimmers crossed the bubble wall parallel to bubble lines. These displacements showed some of the vortices generated by the swimmers with their hands and feet.

Teaching activities: Based on 16 years' experience of teaching swimming propulsion biomechanics it was obvious to us that not only Physical Education undergraduates but even coaches seeking to obtain National Swimming Coach qualifications found difficult to understand these complex theories when they were explained only by references to the literature. It was necessary to devise a teaching method for them that was more interesting and understandable. It had to be a simple demonstration of what happens in these situations. Teaching activities using flow visualization set out in the methods section of this communication where the students participated in the pool after studying the explanations given in the classroom.
After the video recording session at the swimming pool the students should try to analyze the collected video images and they have to answer the following questions: Are vortices generated? What is the size of the vortices? What is the rotation direction of the vortices? How are the vortices generated during underwater undulatory swimming and breaststroke kicking? Are there similarities between the previous kicking techniques? Are the vortices modified when using rubber fins? Are the vortices observed during hand propulsion? What happens when the hand direction is changed abruptly? Are the vortices modified using hand paddles? After grabbing pictures from the video source to the computer they have to write a report explaining the answer to the questions using the pictures. The answers have to be supported by the theory previously studied from the teacher's lessons and from collected bibliography.

CONCLUSIONS: The complex task of teaching the hydrodynamics of a swimmer's propulsion to undergraduate students of Physical Education can be improved if the students have the opportunity to see how water is actively moved when the human propellers are acting in the water. The proposed activities can be used to investigate vortex fluid mechanics principles. As the old adage says "seeing is believing".

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