WAVE DRAG IN HUMAN SWIMMING

David Pease

Australian Institute of Sport, Canberra, Australia

This presentation will examine the influence of wave drag on human swimming performance. Even though wave drag has been measured on ships for nearly a century it is only relatively recently that it has been examined in regard to human swimming. Wave drag has been shown to contribute to up to 50% of the total drag experienced during free swimming so gaining and understanding of it and what factors influence it is valuable to not only scientists, but coaches and athletes alike.

KEYWORDS: biomechanics, depth, angle of attack, gender.

The desire to reduce the level of resistance to movement through water has been present for as long as people have utilised any form of aquatic transport. The ability to move more quickly and more efficiently has numerous benefits in terms of commerce, productivity, superiority in warfare, and improved efficiency of movement. While such benefits principally apply to boats and other water craft they are also advantageous in other applications including human swimming. For example, reducing the amount of resistance (drag) acting on the human body during competitive swimming has distinct benefits in terms of performance and therefore, in these days of professional sport, financial gain. Reductions in the drag force can be achieved by trying to manipulate any of the component types of drag which are primarily skin friction or viscous drag, form and wave drag.

Despite the potential benefits of reducing resistance to moving through water, the bulk of research into the effect of drag on boat hulls was not done until into the latter half of the 19th century with the greatest contributions being made by the work of William Froude, Lord Kelvin, and Osborne Reynolds (Froude, 1874, 1877; Kelvin, 1887; Reynolds, 1883).

Many of the findings and theory developed from this early work were exploited quickly to the benefit of the shipping industry. However, it was not until closer to the middle of the 20th century that some of these theories were applied to human swimming. In particular the resistance caused by the generation of waves or 'wave drag', was not closely examined in swimming until closer to the 21st century. Even today there is still not agreement as to the exact contribution of wave drag to the total drag force on a swimmer, let alone the other principle types of drag encountered in swimming, form and frictional or shear drag.

Recently there has been a significant trend by, primarily, swim suit manufacturers, to incorporate low friction materials into swim suits in order to reduce the viscous drag as well as using compressive garments to alter the shape of athletes and thereby reduce the form drag. However, initial work has demonstrated that during swimming at or near the water surface wave drag may be contributing up to 60% of the total drag experienced by the athlete.

Wave drag is a result of the use of energy to create a wave system by raising or lowering a mass of water as the body moves through the water. The displacement of mass requires mechanical work by the person or vessel. In doing this work on the water, kinetic energy equivalent to that gained by the water is lost to the swimmer thereby reducing the kinetic energy possessed by virtue of forward motion. The reaction force from the water that is absorbing the kinetic energy is experienced as a resistive force, that is, wave drag. This form of drag can account for upwards of 50% of the total drag force (Vennell, Pease, & Wilson, 2006) acting on a human swimmer and is therefore a significant limitation to optimal performance.

To date there has been very little research into the determination of wave drag on human swimmers. This lack of investigation into the wave drag in swimming has been largely due to limitations in the technology available. While many of the techniques utilised in the past have been sufficient to examine the forces acting on ship hulls and other rigid bodies, the dynamic nature of human swimming introduces a substantial increase in the complexity of the fluid flow and therefore the wave patterns and associated drag forces. In fact there have been only a few studies published which have attempted to quantify this force based upon experimental results (Pease & Vennell, 2010, 2011; Toussaint, Stralen, & Stevens, 2002; Vennell et al., 2006). In addition to these studies, others have used more indirect means of determining wave drag based upon some theoretical assumptions as to the percent contribution of wave drag to total drag (Toussaint et al., 2002; Vorontsov & Rumyantsev, 2000; Wilson & Thorp, 2003).

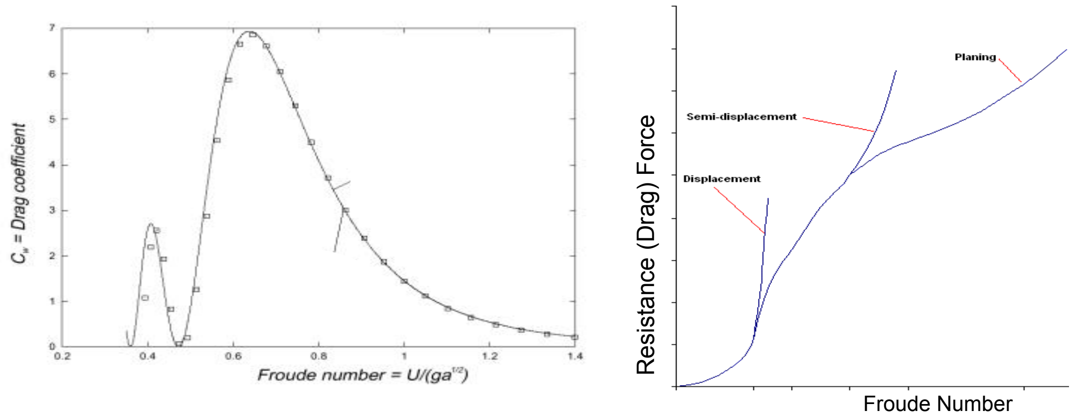

Figure 1: Coefficient of wave drag (left) and total drag (right) with regard to Froude number.

In relation to human swimming, wave drag is dependent upon, among other things, the swimmer's velocity, body shape and movements in proximity to the water surface (Bixler, 2005). As with ship hulls, wave drag in swimming is often expressed as a function of the Froude Number (*Fr)* (Bixler, 2005). The relationship of wave drag coefficient and total drag to Froude number is presented in Figure 1. For human swimmers it has always been assumed that they are true displacement craft and therefore can achieve a *Fr* of approximately 0.42 (Larsen, Yancher, & Baer, 1981). Recent research has reported even higher *Fr* of 0.46 (Kolmogorov, 2008). Maximal *Fr* in this range are limiting in that the required stroking power of a swimmer to reach them increases to the fifth or six power of the velocity (Larsen et al., 1981). Hence, large increases in stroke length or power will only result in small increases in velocity as a consequence of increased wave drag (Larsen et al., 1981; Videler, 1993). However the reduction in slope of the drag curve for a near surfaced towed mannequin at high speeds in Vennell et al, suggests swimmers at Fr=0.45 /2.2 ms^{-1} are near to semi-planning. In fact when a swimming velocity of 2.3 ms^{-1} (approximate velocity of the current 50m freestyle world record) and a representative length of 1.9m are used then the calculated Froude number is approximately .53 and therefore well beyond that value describing a displacement vessel. It is possible, and likely, that during free swimming there are effects on the wave system due to the stroking arms passing through the water surface ahead of the athlete's body. This may in turn alter the characteristic length and therefore the Froude number.

However, until we are able to describe wave drag and it's contributing factors during more fundamental passive conditions our ability to quantify wave drag during active swimming is severely limited due to the greatly increased complexity of free swimming. Therefore, much of the research over the last several years (other than that of Toussaint, et al (2002) , Ohmichi, Takamoto, & Miyashita(1982) and Takamoto, Ohmichi, & Miyashita (1983)) has been focused on describing wave drag characteristics of passive, streamlined, swimmers.

As inertial waves are generally generated when an object is moving near to the surface, one of the most significant influencing factors to wave drag is depth. One of the first studies which attempted to quantify wave drag in human swimming was undertaken by Lyttle et al.(1998) who found a 20% increase in passive drag on real human subjects at the surface as compared to a depth of 0.6m at 2.2ms^{-1}. This difference was attributed to the increase in wave drag. Other than the work of Lyttle, there has been only one other study specifically examining the effects of changes in wave drag with change in depth (Vennell et al., 2006). In their study they determined a contribution of about 50% due to wave drag at 2.25ms^{-1}. Similarly, research investigating the percent contribution of wave drag by determining the work done on the efficiency of fish swimming near the surface and at depth by Webb et al.(1991) calculated an estimated 70% of resistance near the surface was due to the energy dissipation caused by wave generation. An additional finding from this study is that in order to sufficiently eliminate such an energy dissipation the central axis of the fish should be at least 3 body diameters deep. This relative depth criterion also agrees with the findings of Vennell et al. (2006) who suggested that at velocities of around 2.0 ms^{-1} that 2.8 body diameters in depth would allow for the elimination of measurable wave resistance.

Other factors, including body angle of attack and prone vs. supine orientation have also been researched (Pease, 2009; Pease & Vennell, 2010, 2011). The most significant finding with regard to angle of attack was that bodies in an orientation where they had a negative angle of attack (hands lower than feet) showed a lower magnitude in drag force to a positive angle of attack orientation when travelling near the surface. This was most likely due to the flow staying attached to the dorsal surface of the body when in a negative angle of attack orientation thereby minimising the interactions between the flow field and the water surface.

The influence of a prone or supine position is also an interesting aspect due to many athletes adopting one or the other preferentially during competition. The findings of the research showed that the supine orientation exhibited an earlier onset of wave drag than the prone position. This was likely due to the flow field on the ventral surface of the body being more disturbed than the dorsal thereby the flow field interacted with the free surface earlier thereby creating waves earlier and more substantially. Knowing that athletes in a supine position travelling below, but near the water surface, need to travel deeper than those in a prone position to minimise wave drag is important in terms of the performance of competitive swimmers.

Based on the findings in previous research into the relative efficiency between male and female swimmers (Kjendlie & Stallman, 2008) it has been evident that there are differences between male and female forms in terms of the drag force experienced by the two genders. Therefore, the findings of Pease & Vennell (2011) highlight not only interesting differences between male and female anthropometries but also give a direction to possible future research into the influence of body shape on wave drag. In that study it was found that the two geometries exhibited quite different wave drag profiles with changing depth. The more curved female form showed higher drag at depth but, due to a lower wave drag contribution, lower drag near the surface when compared to the less curved male form. While theoretical foundation was found for this finding (Eng & Hu, 1963), it is still necessary to conduct further research using a variety of athletes to experimentally verify the findings. If the findings are substantiated then it may provide some insight into why the more modern racing suits used by athletes, which utilise mid body compression, are beneficial to performance.

Due to the demonstrated significant impact of wave drag on surface and near surface passive movement it is important to obtain better wave drag information on free swimming. There are techniques utilised in marine research such as the longitudinal cut method (Eggers, Sharma, & Ward, 1967) which may be applied to this problem. If these other methodologies in combination with further investigation into shape characteristics can be developed we should be able to expand the research into the influence of actual swimming technique on wave generation and therefore wave drag and hopefully help athletes and coaches develop means of improving their performance in competition.

REFERENCES:

Bixler, B. (2005). Resistance and Propulsion. In J. M. Stager & D. A. Tanner (Eds.), *Handbook of Sports Medicine and Science: Swimming* (Second ed., pp. 59-101). Malden, MA.: Blackwell Science.

Eggers, K. W. H., Sharma, S. D., & Ward, L. W. (1967). An assessment of some experimental methods for determining the wavemaking characteristics of a ship form. *Transactions of SNAME, 75*, 112-144.

Eng, K., & Hu, P. N. (1963). Wave-Resistance Reduction of Near-Surface Bodies (D. o. Defense, Trans.) (pp. 36). Hoboken, NJ: Stevens Institute of Technology, Davidson Lab.

Froude, W. (1874). On Experiments with H.M.S. Greyhound. *Trans. INA, 15*, 36-73.

Froude, W. (1877). On Experiments Upon the Effect Produced on the Wave-Making Resistance of Ships by Length of Parallel Middle Body. *Trans. INA, 18*, 77-97.

Kelvin, L. (1887). Ship Waves. *Proceedings of the Institution of Mechanical Engineers, 3*.

Kjendlie, P. L., & Stallman, R. K. (2008). Drag Characteristics of Competitive Swimming Children and Adults. *Journal of Applied Biomechanics, 24*, 35-42.
Kolmogorov, S. V. (2008). Kinematic and Dynamic Characteristics of Steady-State Non-Stationary Motion of Elite Swimmers. *Russian Journal of Biomechanics, 12*(4), 56-70.
Larsen, O. W., Yancher, R. P., & Baer, C. L. H. (1981). Boat Design and Swimming Performance. *Swimming Technique, 18*(2), 38-44.
Lyttle, A. D., Blanksby, B. B., Elliot, B. C., & Lloyd, D. G. (1998). The effect of depth and velocity on drag during the streamlined glide. *Journal of Swimming Research, 13*, 15-22.
Ohmichi, H., Takamoto, M., & Miyashita, M. (1982). *Measurement of the Waves Caused by Swimmers.* Paper presented at the International Symposium of Biomechanics in Swimming IV; International Congress on Swimming Medicine V, Amsterdam, The Netherlands.
Pease, D. L. (2009). *Wave drag: Implications for performance.* (PhD), University of Otago, Dunedin, New Zealand.
Pease, D. L., & Vennell, R. (2010). *The effect of angle of attack and depth on passive drag.* Paper presented at the Biomechanics and Medicine in Swimming XI, Oslo, Norway.
Pease, D. L., & Vennell, R. (2011). *Comparison of wave drag for both the male and female form.* Paper presented at the International Society of Biomechanics in Sport Porto, Portugal.
Reynolds, O. (1883). An Experimental Investigation of the Circumstances Which Determine Whether the Motion of Water Shall Be Direct or Sinuous, and of the Law of Resistance in Parallel Channels. *Proceedings of the Royal Society of London, 35*, 84-99.
Takamoto, M., Ohmichi, H., & Miyashita, M. (1983). *Wave Height in Relation to Swimming Velocity and Proficiency in Front Crawl Stroke.* Paper presented at the Congress of Biomechanics IX, Waterloo, Ontario, Canada.
Toussaint, H. M., Stralen, M. v., & Stevens, E. (2002). *Wave Drag in Front Crawl Swimming.* Paper presented at the XXth International Symposium on Biomechanics in Sports, Casceres, Spain.
Vennell, R., Pease, D. L., & Wilson, B. D. (2006). Wave Drag on Human Swimmers. *Journal of Biomechanics, 39*(4), 664-671.
Videler, J. J. (1993). *Fish swimming*. London; New York: Chapman & Hall.
Vorontsov, A. R., & Rumyantsev, V. A. (2000). Resistive Forces in Swimming. In V. M. Zatsiorsky (Ed.), *Biomechanics in Sport: Performance Enhancement and Injury Prevention* (Vol. IX, pp. 184-204). London: Blackwell Science Ltd.
Webb, P. W., Sims, D., & Schultz, W. W. (1991). The Effects of an Air Water-Surface on the Fast-Start Performance of Rainbow-Trout (Oncorhynchus-Mykiss). *Journal of Experimental Biology, 155*, 219-226.
Wilson, B. D., & Thorp, R. (2003). *Active Drag in Swimming.* Paper presented at the IX World Symposium Biomechanics and Medicine in Swimming, St Etienne, France.