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Wave drag on human swimmers

Ross Vennell[a,*], Dave Pease[b], Barry Wilson[b]

[a]Department of Marine Science, University of Otago, 310 Castle Street, Dunedin, Otago 9001, New Zealand
[b]School of Physical Education, University of Otago Dunedin, New Zealand

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Abstract

Drag measurements from a towed mannequin show total drag at the surface is up to 2.4 times the drag when fully immersed. This additional drag is due to the energy required to form waves in the wake behind the mannequin. The measurements show that passive wave drag is the largest drag, comprising up to 50–60% of the total at 1.7 m s^{-1}, much higher than any previous estimates. Comprehensive measurements spanning human swimming speeds and tow depths up to 1.0 m demonstrate that wave drag on the mannequin is less than 5% of total drag for tows deeper than 0.5 m at 1 m s^{-1} and 0.7 m at 2 m s^{-1}. Wave drag sharply increases above these depths to a maximum of up to 60% of the mannequin's 100 N total drag when towed at the surface at 1.7 m s^{-1}. The measurements show that to avoid significant wave drag during the underwater sections of starts and turns, swimmers must streamline at depths greater than 1.8 chest depths below the surface at Froude number (Fr) = 0.2, and 2.8 chest depths at $Fr = 0.42$. This corresponds to speeds of 0.9 and 2.0 m s^{-1}, respectively, for a chest depth of 0.25 m and toe to finger length of 2.34 m.

Keywords: Swimming; Wave; Drag; Measurement

1. Introduction

Swimmers and vessels travelling on the water's surface generate waves which form a wake behind them. When travelling at high speed, as measured by the Froude number (Fr), a large proportion of the drag on surface vessels is due to the energy required to create these waves (Van Manen and Van Oossanen, 1988). Elite swimmers also travel at high Fr numbers and the aim of this paper is to give the results of fundamental research which demonstrates that wave drag is the largest component of the drag they experience when at the surface.

There are three main types of drag on surface vessels; viscous or skin friction drag, form drag associated with the turbulent wake of the vessel and wave drag. Wave drag is due to the energy required to create the transverse and divergent waves which lie within a 39° sector behind the vessel. The drag is dependant on the ratio of its speed to that of a water wave with a wavelength equal to the vessel's length, i.e. the Froude number

$$Fr = \frac{V}{\sqrt{gL}},$$

where V = vessel speed, $g = 9.81$ m s^{-2}, L = length of the vessel. A typical total drag curve for a vessel is shown in Fig. 1. Above $Fr = 0.25$ the drag increases rapidly due to the increasing importance of wave drag. Drag curves may display "bumps" at particular speeds due to constructive and destructive interference of the waves generated at each change in cross-section of the hull. Around $Fr = 0.42$, the vessel's speed matches that of a wave which has a wavelength equal to the length of the vessel. This is the so-called "hull speed", the maximum that can be achieved as a displacement vessel. The drag increase is typically less rapid above $Fr = 0.45$, as the vessel generates hydrodynamic lift, reducing its displacement as it rises to a planing condition. A 1.8 m

*Corresponding author. Tel.: +64 3 479 8307; fax: +64 3 479 8336.
E-mail address: rvennell@otago.ac.nz (R. Vennell).

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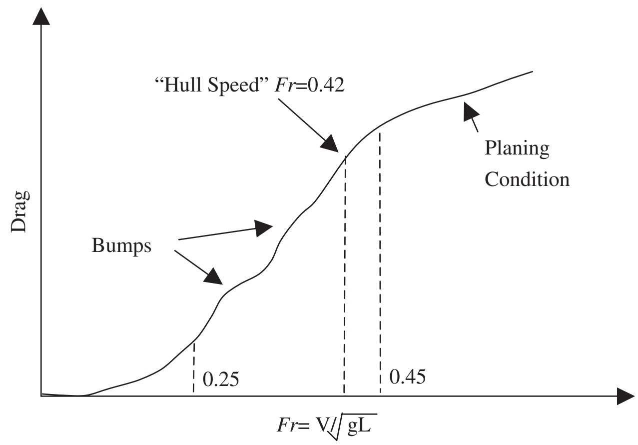

Fig. 1. Schematic drag curve for a surface vessel versus Froude number. Based on Van Manen and Van Oossanen (1988).

tall elite swimmer at $1.8\,m\,s^{-1}$ has $Fr = 0.42$, and with arms extended to a total length of 2.3 m, has $Fr = 0.40$, thus wave drag would be expected to constitute a large proportion of their total drag.

Several attempts have been made to quantify wave drag on swimmers. Vorontsov and Rumyantsev (2000) suggested that 5% of drag was due to waves at $2\,m\,s^{-1}$. Toussaint et al. (2002) used the Measurement of Active Drag (MAD) system measurements to estimate that wave drag had a greater contribution, 21% at $1.9\,m\,s^{-1}$. Wilson and Thorp (2003) used power law fits to estimate that wave drag contributed between 10% and 20% of active drag at $1.0\,m\,s^{-1}$ and between 35% and 45% at $2.0\,m\,s^{-1}$. Lyttle et al. (1998) towed 40 swimmers using a pulley system at velocities from 1.6 to $3.1\,m\,s^{-1}$ and depths between the surface and 0.6 m. They found that drag was 20% lower at 0.6 m depth than at the surface when towing at $2.2\,m\,s^{-1}$.

A deeply immersed solid body towed horizontally does not generate surface waves and drag is mainly due to skin friction and form drag. Viewed from a perspective moving with the body, the effect of the body is to force fluid to flow around it, distorting the flow near the body. In some regions, the distortion increases velocities and in others reduces velocities relative to the undisturbed flow, with the size of the velocity distortions decreasing with distance from the body. When the body moves close enough to the water's surface for the distorted flow to impinge on the surface the pressure changes, due to the Bernoulli effect, associated with the distortion cause both depressions and elevations in the water's surface above the body. These in turn create a wave wake and thus the body begins to experience wave drag. The closer the body is to the surface, the larger the depressions and elevations, leading to greater wave drag. Wave drag is an additional drag experienced near the surface which is not present when deeply immersed, thus total drag would be expected to increase as the body approaches the surface. Wave drag is typically assumed independent of skin and form drag and thus the difference between the total drag measured when towed near to or at the surface and the drag when deeply immersed is an estimate of the drag due to waves.

2. Measurements

The measurements were made in a 2.5 m wide, 1.5 m deep flume with a 10 m long working section capable of water speeds up to $3\,m\,s^{-1}$. The towing rig consisted of a forward strut joined to a horizontal towing rod in series with a load cell. To keep it horizontal, the rod passed through a frictionless sleeve in a rear strut (Fig. 2). The mannequin was attached to the rod 1 m behind the rear strut to reduce the effect of the flow around the struts on the mannequin. Underwater observations of the mannequin showed that the toe depth, which was not fixed, was very stable during tows. Tow depth was varied by vertically adjusting the horizontal towing rod. A Marsh McBinney Flow Mate 2000 velocity meter was attached on the rear strut just above the horizontal towing rod. The flume's velocity profiles both vertically and horizontally have been comprehensively measured and show variation of less than $0.1\,m\,s^{-1}$ outside of the regions within 20 cm of the walls and floor. With no mannequin in the flow the water surface was flat within 2 cm at $2.6\,m\,s^{-1}$, much less than the 15 cm wave generated by the mannequin at these speeds.

A Sensotec Model 31/4267-06 tension load cell was placed between the forward strut and the horizontal rod

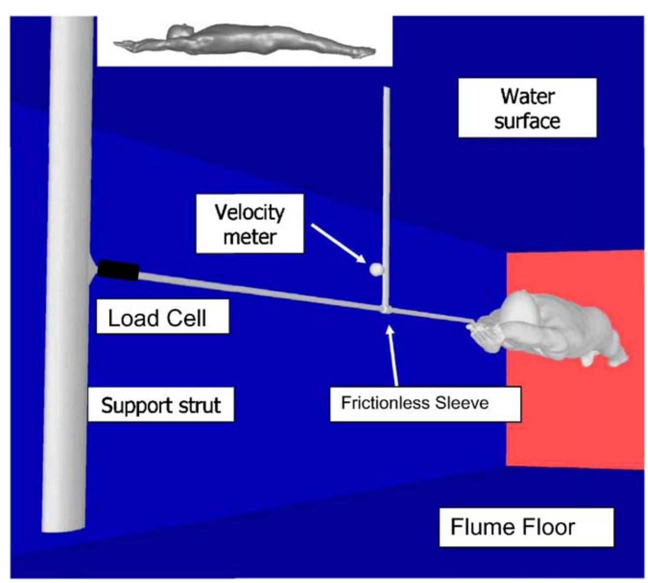

Fig. 2. Experimental setup of towing rig. A load cell was mounted between the horizontal towing rod and the front support strut. The male mannequin was towed face up with arms extended. Inset shows mannequin's streamlined posture.