The Physics of Rowing

Chris Pulman
Gonville & Caius College, University of Cambridge

Relatively little is known about the exact mechanisms that explain the motion of rowing boats. This essay discusses some of the physical processes that govern the motion of eight-oared boats (VIII). Boats move because momentum is transferred to the water by the rowers and their oars, causing the boat to move forwards; a process complicated by the motion of the rowers within the boat itself. Many forms of drag are manifest in resisting the motion of the boat such as skin, form, wave, aero-dynamical and inertial. An analysis of each concludes that it is usually inertial drag which has the greatest effect, although both wave and aero-dynamical drag can also be significant, depending on the weather conditions and speed of the boat. Moreover, due to the resistive drag, in order to double the boat speed eight times as much effort is required from the rowers. Although classical ship analysis shows that the VIII will be statically unstable, an appreciation of the flow of water around the bows provides an explanation for the stability of moving boats. Finally, the mechanisms of the rowing stroke are investigated. It appears that lift forces – acting in a horizontal direction - provide the main means of acceleration in the early and late stages of the stroke, while it is the movement of water by the blade which imparts momentum to the boat during the middle part of the stroke.

I. Introduction

This essay presents a discussion of the physical processes that govern the motion of eight-oared boats (VIII), although the physics may also apply to other rowing boats. An VIII is a narrow boat (70cm maximum width, 20m in length) powered by eight rowers each holding an oar, steered by a coxswain. The rowers are mounted on sliding seats with their feet attached to the boat by restraints.

The basic principle of rowing is quite simple; momentum is transferred to the water by pulling on the oar and pushing with the legs, which causes the seat to slide backwards. The oars pivot on "riggers" which lever the water backwards. However, the motion of the boat is complicated by the movement of the rowers within the boat, resulting in it moving fastest when the oars are out of the water and the rowers are moving towards the stern of the boat.

Opposing the motion of the boat is drag which appears in several forms: skin, inertial, aerodynamic and wave. The effects and applicability of each type of drag are considered.

The balance properties of an VIII are discussed in the context of classical ship theory and an appreciation of the flow of water around the bows of the boat. Finally, the rowing stroke is examined and the mechanisms of lift and reversal of the oar blade, caused by the movement of water, are compared.

II. Propulsion

Momentum is imparted to the water by the oar, resulting in the boat accelerating in the opposite direction. Although the blade appears to "lock on" in the water, it must move the water in the opposite direction to the motion of the boat in order to conserve momentum. As it is energetically efficient to move a large amount of water slowly, rather than a small amount quickly, blades have a large surface area in order to maximise the water displaced.

The basic principles of the propulsion of a boat are, however, complicated by the variability of the centre of mass (CM) of the rowers caused by the sliding seats (fig. 1). When the oars are in the water, this relates to the momentum imparted to the water. In the recovery phase, when the oars are not in the water and the rowers move towards the stern of the boat, momentum conservation (equation 1) requires that the boat *surges* forwards. This motion is clearly visible when viewing a rowing boat.

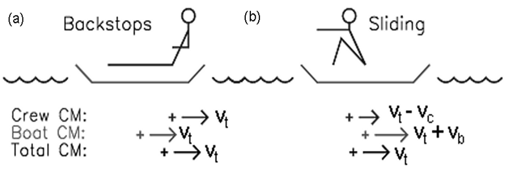

FIG.1. (a) The crew is at "backstops", the end of the stroke, and the blade has just been removed from the water; the crew and boat are at rest with respect to each other so they move with the velocity of the CM, v_t. (b) The crew is sliding forwards to the stern of the boat at a speed v_c which causes the boat to surge forward with extra velocity v_b.

$$m_c v_t + m_b v_t = m_c\left(v_t - v_c\right) + m_b\left(v_t + v_b\right)$$

$$\Rightarrow v_b = \frac{m_c}{m_b} v_c \qquad \textbf{(1)}$$

m_c, v_c, m_b and v_b are the masses and velocities of the crew and the boat respectively and v_t is the boat speed immediately after the blades have been removed from the water.

The equations of motion of a rowing boat (Brearley and de Mestre 1996) are, for the power phase:

$$\left(m_b + m_c\right)\frac{du}{dt} = E(t) - m_c H_1(t) - R(t) \qquad \textbf{(2)}$$

and the recovery phase:

$$\left(m_b + m_c\right)\frac{du}{dt} = m_c H_2(t) - R(t) \qquad \textbf{(3)}$$

where u is the boat speed, $E(t)$ is the effort force exerted on the oars by the rowers, $R(t)$ is the total drag resistance to motion and $H_1(t)$ and $H_2(t)$ are the accelerations of the rowers' bodies during the power and recovery phases respectively. Brearley and de Mestre suggest that the motion of the rowers can be taken as a half-cycle of simple harmonic motion. Lazauskas (1997) showed that there are three primary forms of $E(t)$ (fig. 2) and computer simulations (van Holst 2004) have shown that the symmetrical form (fig. 2ii) is the most energetically efficient. The drag resistance is discussed in section III.

Effort $E(t)$ is transmitted from the rower to the water through the oars which, in the frame of the boat, are class 1 levers (fig. 3). The load is:

$$L = E\left(\frac{b}{a}\right) \qquad \textbf{(4)}$$

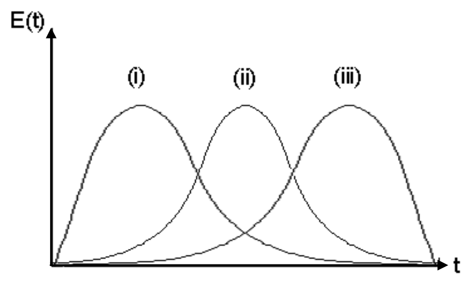

FIG. 2. Force curves $E(t)$ for the power phase of the stroke. (i) Peak pressure applied at the beginning of the stroke; (ii) Peak pressure applied during the middle of the stroke, with the effort symmetrical about that point; (iii) Peak force applied at the end of the stroke.

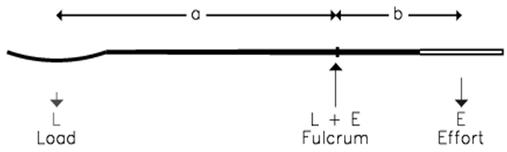

FIG.3. A class 1 lever, effort E is applied at the oar handle and is transmitted through the fulcrum to the load L at the blade.

The work done by the rower is transferred to the water as kinetic energy, causing it to move past the boat. However, the observer on the river bank views the oar as a class 2 lever, with the blade acting as a fulcrum and the boat being levered past the stationary blade (fig. 4).

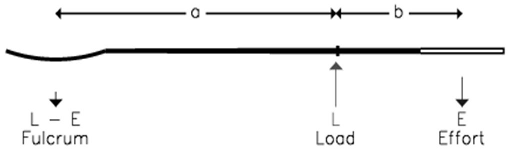

FIG. 4. A Class 2 lever. The effort E is applied at the oar handle, but the blade acts as the fulcrum and the load at the "rigger" (L) is moved.

III. Resistance

Like any body moving in a fluid, the motion of rowing boats is opposed by resistive drag; momentum is transferred to the water by the passing of the boat. Characteristic types of drag are skin, inertial, aerodynamic and wave. Skin drag arises from the formation of a shear boundary layer around the hull arising from the viscosity of the water. This causes the boat's effective mass to increase as water is dragged along by the boat. Inertial drag arises due to the water in front of the boat being accelerated, resulting in the boat's momentum decreasing. Wave drag represents the dissipation of energy in the creation of waves. The shape of the hull is a significant factor since the drag is a function of the wetted area of the boat.

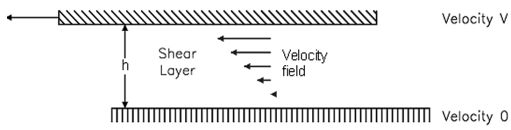

FIG. 5. The top slab represents the boat moving at velocity v at height h above the river bed. A shear layer forms between the two which gives rise to a velocity field caused by the water being dragged along by the passage of the boat.

For boats moving in shallow water, viscous drag is predominant (fig. 5). The fluid adjacent to the boat forms a boundary layer and a shear is set up in the fluid with a velocity gradient v/h, modelling the bottom of the boat as a flat sheet. The presence of a boundary layer means that the boat is dragging water along, increasing its effective mass. The resistance per unit area acting on the boat due to the fluid is then

$$\frac{R}{A} = \eta\frac{dv}{dz} = \eta\frac{v}{h} \qquad \textbf{(5)}$$

However, this analysis applies only to shallow water (<10cm).

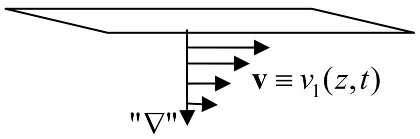

FIG.6. Slab representing the underside of the boat. The downward pointing arrow represents the direction of the velocity gradient (ie "∇") while v_1 represents the velocity field of the fluid.

Generally, as the boat moves through stationary water, the fluid in contact with the bows is immediately accelerated to the boat speed, *v*, but the shear layer only extends downwards as the vorticity Ω diffuses away from the boat (equation 6, fig. 6).

$$\Omega = \nabla \times \mathbf{v} \qquad \textbf{(6)}$$

So the water is accelerated in accordance with the diffusion equation (7).

$$\rho\frac{\partial v_1(z,t)}{\partial t} = \eta\frac{\partial^2 v_1(z,t)}{\partial z^2} \qquad \textbf{(7)}$$

An approximate solution of this equation gives the width Δ of the boundary layer at a time *t* as

$$\Delta = \sqrt{\frac{\eta t}{\rho}} \qquad \textbf{(8)}$$

This indicates that resistance is proportional to boat speed; however, within water, equation 8 implies that during one stroke the boundary layer only diffuses ~2mm which is not particularly significant.

In contrast, the high Reynolds number of water implies that the primary resistance impeding the motion of the boat is the inertial drag. The pressure exerted by the fluid on the boat is $\frac{1}{2}\rho v^2$ where *v* is the speed of the water relative to the boat (i.e. the boat speed). This gives the drag resistance as

$$R = \frac{1}{2}C_D \rho v^2 A \qquad \textbf{(9)}$$

where *A* is the area of the boat exposed to the stream flow and C_D is the drag coefficient of the boat, defined as the ratio of actual drag to ideal drag. This gives more acceptable values for the drag resistance. There are also implications for power requirements; the momentum change of the water as a result of the passage of the boat in a time *t* is:

$$\Delta p = \rho A v t \qquad \textbf{(9)}$$

So the power required to maintain constant velocity *v* is then:

$$\int_0^t F dt = \int_0^v \rho A v t dv$$
$$\Rightarrow F = \frac{1}{2}\rho A v^2$$
$$\therefore P = Fv = \frac{1}{2}\rho A v^3 \qquad \textbf{(10)}$$

Thus, eight times more power is required to double the boat speed. Indeed, this is actually sensed when rowing.

In strong headwinds aerodynamic drag can severely resist the motion of the boat, although its usual impact is small. Drag due to air resistance has the same form as equation 10; however, the smaller density of the air lessens its contribution. The velocity of the boat is then replaced by sum of the boat and wind velocities. It is clear that for strong headwinds air resistance rapidly becomes significant. The drag is proportional to the area exposed to the flow – i.e. the projected area of the rowers into the wind, although this is a poor approximation as each rower shields those rowers behind, causing complex air-flows which affect the calculation.

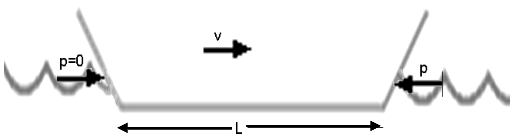

FIG. 7. The length of the boat *L* is such that the waves to the left of the boat are at a minimum. In contrast, those at the right of the boat are at a maximum resulting in resonant losses due to the pressure difference between the two ends of the boat.

A rowing boat is narrow and is not able to generate large waves. However, if the length of the boat, L, is such that

$$L = \frac{2n+1}{2}\lambda \qquad \textbf{(11)}$$

where λ is the wavelength of the waves generated, then resonant losses occur (fig. 7). To avoid this situation the boat should not travel at speeds

$$v = \sqrt{\frac{Lg}{(2n+1)\pi}} \qquad \textbf{(12)}$$

At these speeds the energy dissipation due to waves is maximal and so wave drag is significant. The Froude number, F, indicates the significance of wave drag and for an VIII travelling at $5 ms^{-1}$ (i.e. 2 km racing speed) it is:

$$F = \frac{v}{\sqrt{gL}} = 0.35 \qquad \textbf{(13)}$$

which corresponds to a local minimum in the wave drag (fig. 8), so although wave drag is certainly present, it is not significant for a racing boat.

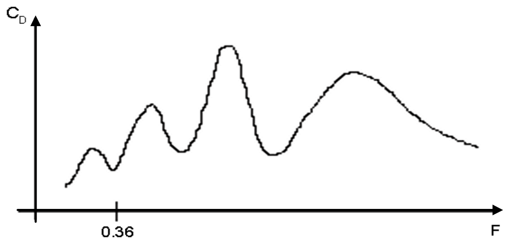

FIG. 8. Variation of the wave drag C_D with the Froude number F. A boat moving at race pace minimises the wave drag locally.

IV. Balance of rowing boats

Racing boats have their centre of gravity (CG) some distance above their centre of buoyancy (CB – the CG of the submerged portion of the boat). Since the boat is partially submerged, an upthrust acts vertically through the CB and the meta-centre (MC – the geometrical centre of the boat). If the boat starts to roll, then a couple is generated due to the weight of the boat and rowers, which acts at the CG, and the upthrust, which acts at the CB. If the CG is below the MC, then the couple is in the opposite direction to the roll, and the boat returns to an upright position. If, however, the CG is sited above the MC, the couple acts in the same direction as the initial roll, and provides positive feedback: the boat tips over (fig. 9). The limit of stability is

$$z = \frac{I}{V} \qquad \textbf{(14)}$$

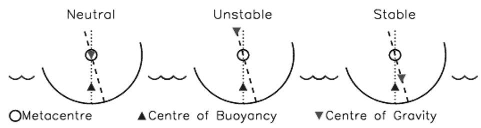

FIG. 9. When the CG is cited at the MC the balance is neutral and the boat is stable. Similarly, when the CG is sited below the MC the boat is also stable. However, when it is sited above the MC a turning moment is generated for any small displacement from equilibrium and the boat will roll over (it is unstable).

Where z is the limiting distance of the CG over the CB, I is the moment of inertia of the waterline shape of the boat about the axis of roll, and V is the volume of fluid displaced. The CG for an VIII is approximately 10cm above the seats, so equation 14 illustrates that a wide-bottomed boat with a shallower hull-curvature (and larger moment of inertia), is more stable than a narrow one, taking longer to roll over. However, the increased surface area produces a higher drag, so most racing shells tend to be quite narrow. Although a stationary empty boat has been shown to be stable, measurements (Kerr 1996) show that for an VIII with crew on board the CG is ~15cm above the MC (just above the height of the seats) causing inherent instability.

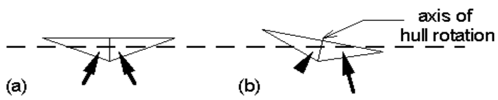

FIG. 10. (a) The boat is stable since there is a balanced water flow exerting reaction forces on the hull. (b) The boat is tilted and the unbalanced water flow causes the boat to return to its level position.

Whereas instability of a static boat is often observed; a moving boat tends to balance well with little correctional input from the rowers, such as leaning or altering the hand-heights of the oars. As the bows move through the water, around 400kg of water is displaced per second for a boat travelling at $5 ms^{-1}$. Although much of this water is moved away by the waves generated, significant forces normal to the hull result due to the momentum change caused by the passage of the bows. In particular, the V-shaped bottom of the bows produces turning moments which cause the boat to return to the upright position (i.e. – the *moving* boat is in a stable equilibrium, fig. 10). The greater the volume of water displaced per second – i.e. the greater the speed – the more significant this effect becomes.

V. The rowing stroke

The function of the stroke is to transfer the work done by the rowers into kinetic energy of the boat. The mechanisms behind this transfer of momentum, however, are relatively complex. Indeed, it has been a subject of controversy within the rowing community as to the exact interaction of the blade with the water. It is generally accepted that, at the beginning and end of the stroke, lift – acting in a horizontal direction - provides the main impetus for propulsion. However, during the middle of the stroke the resistance of water on the blade provides propulsion. It is not clear which of these mechanisms is predominant.

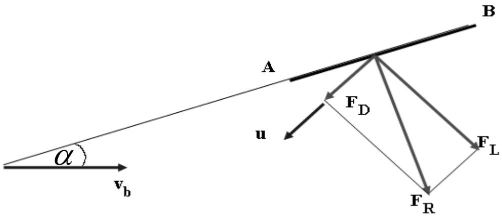

FIG. 11. Diagram of the oar. AB is the blade, **u** is the velocity of the water, α is the angle between the oar and the side of the boat, v_b is the velocity of the boat and F_R is the force acting on the blade resulting from the drag (F_D) and the lift (F_L) forces.

At shallow angles α (fig. 11), the blade acts like a hydrofoil and the resultant force on the blade is composed of a drag force F_D and a lift force F_L. As water is directed to one side of the blade a reaction force results - the lift. In contrast to an aeroplane wing, the flow of the water around the blade results in the lift force acting horizontally, rather than vertically. The lift does no work, so if it is maximised while the drag force is minimised then little energy is wasted and the boat moves more quickly. Under these conditionss, however, the longitudinal component propelling the boat is rather small. It has been suggested by Brearley (1998) and van Holst (2004) that altering the angle of attack (fig. 12) would maximise this effect in the first part of the stroke but have a negative effect in the latter part. If the rowers aim to produce peak power at the beginning of the stroke altering this angle may provide an advantage, although this is not energetically efficient (fig. 2). The drag and lift forces are:

$$F_D = \frac{1}{2} C_D \rho A v^2 \qquad \textbf{(15)}$$

$$F_L = \frac{1}{2} C_L \rho A v^2 \qquad \textbf{(16)}$$

Where C_D and C_L are the drag and lift coefficients and v is the velocity of the undisturbed flow. The directions of F_L and F_D are determined by the direction of circulation of the vortices. It can also be seen from fig. 11 that the C_D and C_L are related by:

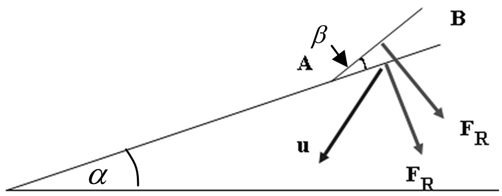

FIG. 12. The angle of attack β has been increased so that the longitudinal component propelling the boat is larger at the beginning of the stroke.

$$\frac{C_D}{C_L} = \tan\alpha \qquad \textbf{(16)}$$

As α increases throughout the stroke F_D increases and the lift decreases until $\alpha \approx 40^o$ when the blade stalls in the water – in the same way an aeroplane stalls in the air - and lift is zero. At this point resistance against the blade through the exchange of momentum with the water provides the mechanism for propulsion. When α increases to approximately 110^o the blade again begins to experience lift until the end of the stroke.

Young (1997) studied this sequence of events in detail. As the blade catches at the beginning of the stroke a *slow-moving* vortex is shed at the end of the blade. This results in a *bound* vortex (with the opposite sense) forming around the blade, providing lift until the blade stalls in the flow. At this point the *fast-moving bound* vortex around the blade is shed. At the end of the middle phase of the stroke, a further *fast-moving* vortex is shed from the end of the blade as another *bound* vortex (with the opposite sense) forms around the blade providing lift. At the end of the stroke this is then shed (fig. 13).

Interestingly, the blade tip moves approximately 10cm in the direction of motion of the boat by the end of the stroke. Furthermore, during the stroke it can reach as far forward as 40cm. Also, the observer on the bank views the blade as being stationary when the blade stalls. The blade velocity throughout the stroke was shown to vary significantly; when experiencing lift it was directed in the direction of motion of the boat (with a maximum velocity of $3ms^{-1}$). In contrast, when the blade was stalled it moved backwards (with a maximum velocity of $-1ms^{-1}$) which is consistent with momentum exchange with the water. Significantly, this implies that the maximum dynamic pressure generated in the lift phase is nine times larger than that during the momentum exchange phase. However, the longitudinal component of this force is small during the lift phase but is large during the momentum exchange phase. Consequently, it

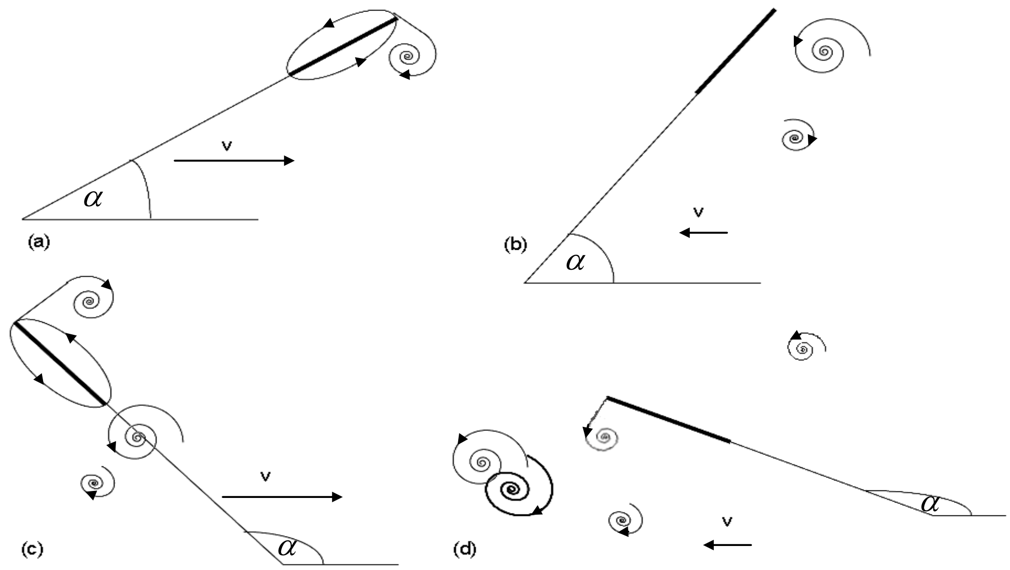

FIG. 13. (a) At the beginning of the stroke a small leading-edge vortex is shed causing the creation of a lift-inducing vortex (of the opposite sense) around the blade. (b) The angle α increases to the point where the blade stalls in the water so the large vortex encapsulating the blade is shed. (c) The blade angle once again allows lift and so a large leading-edge vortex is shed, forming a further counter-sense vortex around the blade. (d) At the end of the stroke the blade ceases to move and the small vortex around the blade is shed. The result at the end of the stroke is two small slow-moving vortices formed at the beginning and end of the stroke and a fast-moving twin-vortex system formed during the middle of the stroke. The longitudinal velocity of the blade v relative to the water is shown in each figure.

is unclear which mechanism provides the dominant contribution to propulsion.

It is clear, however, that lift is a more efficient mode of propulsion since it involves the movement of a large amount of water with a small velocity, while propulsion derived from resistance involves the movement of a small amount of water at a large velocity. This interpretation of the stroke helps to explain why it is important for rowers to have a "fast catch"; the faster the blade enters the water the more quickly the leading-edge vortex can be shed and lift provided to the blade. This also applies at the "finish" where removing the blade quickly prevents significant drag upon it. The blade has stopped moving forwards through the water so it has shed its vortex and is susceptible to drag resistance; quick removal minimises this effect.

VI. Conclusion

Although the motion of rowing boats appears quite simple, it is, in fact, somewhat complicated. Not only does the motion of the rowers affect the speed of the boat, but also the river conditions and the way the stroke is taken.

It is suggested that for shallow rivers skin drag and viscous effects will have a significant contribution. However, in most cases the major contribution is due to the inertial drag of the boat. Similarly, boat length must be carefully considered to avoid resonant losses to wave drag. Coincidently, it has been shown that a boat at race-pace minimises the wave drag. However, further research into changing wave drag conditions and also the effects of aerodynamic drag would be useful. Headwinds and crosswinds cause complex turbulence effects which may have a significant effect upon the boat speed.

The differential balance characteristics between static and moving boats have been discussed. Although a static VIII was shown to be unstable, a moving boat appears to be dynamically stable. This was explained by considering the local exchange of momentum with water as it flows either side of the bows.

It was thought that two mechanisms are responsible for the propulsion of the boat during the stroke. In the earlier and later stages of the stroke, when the angle between the oar and the boat is small, the blade acts as a hydrofoil. A leading-edge vortex is discharged causing the creation bound vortex around the blade which provides lift in a horizontal direction, moving the blade forwards. In contrast, as the blade reaches the middle of the stroke it stalls in the water. In this phase, the movement of a small amount of water at high velocity produces acceleration. It has been shown that the dynamical pressure generated by the lift mechanism is nine times larger than that generated from simply moving the water with the blade during the middle of the stroke. However, momentum transfer to the boat is more efficient during the middle of the stroke because the longitudinal component of the pressure is large. In contrast, for small blade angles it is quite small. An exact comparison is not appropriate until further research into the longitudinal component of the lift force is available. However, the mechanisms described here explain why it is advantageous for the rower to perform a quick catch and a quick finish, as the time to shed a vortex (in the first case), and the time the blade undergoes drag (in the second case), is minimised.

In summary, the motion of rowing boats has been discussed. The methods of propulsion, while derived from the motion of the rower, are variable. Furthermore, the drag forces that oppose the motion of rowing boats are complex, and their applicability often depends upon the inherent conditions. Finally, rowing boats have been shown to balance stably when moving. Further research into these phenomena is required to add to our understanding of the motion of rowing boats; in particular, the effects of aerodynamic drag, lift forces upon acceleration, and 3D effects such as twisting of the oar blade.

1. Dudhia, *Basic Physics of Rowing*, http://www.atm.ox.ac.uk/rowing/physics/ (2001)
2. L. Lazauskas, *A Performance Prediction Model of Rowing Races*, http://www.cyberaid.net/library/rowing/stroke.htm (1997)
3. M. van Holst, *Simulation of Rowing*, http://home.hccnet.nl/m.holst/report.html (2004)
4. E.O. Tuck and L. Lazauskas, *Low Drag Rowing Shells*, http://www.cyberaid.net/library/rowing/misbond/misbond.htm (1996)
5. S. Kerr, *Balance of Racing Rowing Boats*, http://www.btinternet.com/~furnivall.sc/fscbrb.htm (1998)
6. B. Carpenter, B. Krum, J. Thrasher, M. Epley, S. Nguyen, T. Pope, T. Blankenship, S. Sutherland, M. Klara and P. Tidewll, *Rowing Rigger Design*, http://filebox.vt.edu/eng/mech/tidwell/me4016/final/final.html (1997)
7. K. Young, *Hydrodynamic Lift in the Sculling Stroke*, http://www.phys.washington.edu/~wilkes/post/temp/phys208/scull.lift.html (1997)
8. M. Brearley and N. J. de Mestre, *Modelling the Rowing Stroke and Increasing its Efficiency*, 3rd Conf. Mathematics and Computers in Sport, Bond University, Queensland, Australia (1996)
9. J. Local, *Discussion*, Cambridge University Boat Club (2004)
10. M. Warner, *Lectures on Fluids,* http://www.tcm.phy.cam.ac.uk/~mw141/pt2/fluids.html (2004)