2008

Rowing : the drive behind a complex sport

Paul Conlin
Lehigh University

Recommended Citation

Conlin, Paul, "Rowing : the drive behind a complex sport" (2008). *Theses and Dissertations.* Paper 1030.

Conlin, Paul

Rowing; The Drive Behind a Complex Sport

January 2009

Rowing: The Drive Behind a Complex Sport

By

Paul Conlin

A thesis presented to Lehigh University

in Candidacy for the Degree of

Master of Science

in

Mechanical Engineering

December 2008

Certificate of Approval

This thesis is accepted and approved in partial fulfillment of the requirements for the Master of Science.

Dec 2, 2008

Date

Thesis Advisor

Department Chair

Acknowledgements

I would like to thank my advisor, Professor Kazakia, for his guidance, reviews of my research, and his support as an advisor during my tenure at Lehigh University. I would also like to thank my wife for her support in both my frustrations and triumphs. In addition, thanks to my company Wyle Laboratories for giving me the opportunity to pursue this degree. Finally, I would like to thank my father for his help in the editing of this thesis and ensuring that I wrote intellectually and coherently.

Contents

1) Introduction 1

2) The Physics of Rowing 5

3) Blade Work 23

- 3a. Blade Theory 23
- 3b. Blade Manufacturing 31
- 3c. Blade Testing 34

4) Mechanical Efficiency 56

5) Rowing On Uncertain Waters 70

- 5a. Asynchronous Rowing (Rowing Out of Phase) 70
- 5b. Back Splash 80
- 5c. Effects of Rigging: Spread 84
- 5d. Oar Bending 86

6) Rowing Out of the Wake 90

References 95

Appendix A) The Effects of the Properties of Water 97

List of Figures & Tables

FIGURE/TABLE	Page
1a: The Catch 1b: The Finish	6
2: Type 1 Lever	9
3: Basic Rowing Free Body Diagram	10
4: Rowing Free Body Diagram of the Forces on an Oar	12
5 and 6: Velocity Components of the Blade	13
7: Actual Motion of the Blade at Various Stroke Rates	14
8: Velocity of the Shell During Over Time	17
9: U.S. Patent for an Oar	24
10: Diagram Explanation of Stalling	25
11: Tilt Angle and Cant Angle Defined	26
12: Comparison of Tilt Angle for a Rowing Blade and an Airfoil	27
13: Loading Profile for Various Concept 2 Blade Designs	30
14: Tulip Blades	34
15: Hatchet Oars	35
16: Dreher's LS1999	38

List of Figures & Tables

FIGURE/TABLE	Page
1a: The Catch 1b: The Finish	6
2: Type 1 Lever	9
3: Basic Rowing Free Body Diagram	10
4: Rowing Free Body Diagram of the Forces on an Oar	12
5 and 6: Velocity Components of the Blade	13
7: Actual Motion of the Blade at Various Stroke Rates	14
8: Velocity of the Shell During Over Time	17
9: U.S. Patent for an Oar	24
10: Diagram Explanation of Stalling	25
11: Tilt Angle and Cant Angle Defined	26
12: Comparison of Tilt Angle for a Rowing Blade and an Airfoil	27
13: Loading Profile for Various Concept 2 Blade Designs	30
14: Tulip Blades	34
15: Hatchet Oars	35
16: Dreher's LS1999	38

17: Concept 2's Vortex Generators (VGs)	39
18: Dreher's Apex Design, vs Dreher's BB21	42
19: Force Comparison Between Cant Angles of 0° and 5°	44
20: Results from Concept 2's Testing of Two Different Designs	47
21: The LMF's Testing Setup	51
22: Samples of LMF Meshes (M12e4 Left and M12e5 Right)	52
23 and 24: Hydrodynamic Force Curve & Hydrodynamic Torque	54
25a: Velocity vs Blade Efficiency 25b: Stroke Rate vs Boat Efficiency	60
26: Force and Slip Vectors Over the Blade's Path	62
27a: Efficiency vs. Oar Angle 27b: Power vs. Oar Angle	64
28: Comparison of Cabrera & Ruina's Model for Blade Force and Velocity with Testing Data	68
29: 2 Phase Rowing Detail	71
30: Comparison of the Velocities of Single Phase and 2-Phase Rowing	74
31: Power Distributed Through the Foot Stretcher	77
32: Description of Catch Angle	82

17: Concept 2's Vortex Generators (VGs)	39
18: Dreher's Apex Design, vs Dreher's BB21	42
19: Force Comparison Between Cant Angles of 0° and 5°	44
20: Results from Concept 2's Testing of Two Different Designs	47
21: The LMF's Testing Setup	51
22: Samples of LMF Meshes (M12e4 Left and M12e5 Right)	52
23 and 24: Hydrodynamic Force Curve & Hydrodynamic Torque	54
25a: Velocity vs Blade Efficiency 25b: Stroke Rate vs Boat Efficiency	60
26: Force and Slip Vectors Over the Blade's Path	62
27a: Efficiency vs. Oar Angle 27b: Power vs. Oar Angle	64
28: Comparison of Cabrera & Ruina's Model for Blade Force and Velocity with Testing Data	68
29: 2 Phase Rowing Detail	71
30: Comparison of the Velocities of Single Phase and 2-Phase Rowing	74
31: Power Distributed Through the Foot Stretcher	77
32: Description of Catch Angle	82

33: Visual Description of Spread	85
34: Bending Angles	88
35: Men's 8 Velocity Compared to Water Temperatures	98

Tables:

Table 1: Experimental Data for Various Rowers	20
Table 2: Results of Efficiency Data Collected for a Men's 8 Crew	65

33: Visual Description of Spread	85
34: Bending Angles	88
35: Men's 8 Velocity Compared to Water Temperatures	98

Tables:

Table 1: Experimental Data for Various Rowers	20
Table 2: Results of Efficiency Data Collected for a Men's 8 Crew	65

Abstract

A mechanical overview of rowing is presented. A general review of the physics of rowing is discussed. Specific attention is paid to the blade-water interaction. State of the art models for developing oar blades and testing their effectiveness are reviewed. Overall efficiency of both the rowing machine and the blade are addressed. Using this information, several long standing debates about rowing are addressed and finalized.

Chapter 1: Introduction - Starting Sequence

"300 meters left! Take up the rate," yells the coxswain. Although exhausted from the previous 1,700 meters, the rowers respond. The stroke rate increases from 36 strokes per minute to 40. This is similar to trying to jump while lifting a weight off the ground, 40 times in a minute. "I have their stroke seat. Make them cry," demands the coxswain as the boat moves into first. At this time, the rower cares nothing of physics and is just concentrating on using his/her body to drive the boat as fast as possible. However, without the engineers who designed the boat and oars, the rower could lose this race.

To define rowing from an engineering standpoint there are several aspects that need to be defined. The forces that act upon the boat causing it to move forward must be defined. This includes the blade force, the force of the rower's body, as well as the drag forces acting on the shell and blade.. Velocity equations also must be defined to determine the speed of the shell especially when adjustments are made to the rigging of the boat or to the crew's strategy. The definitions discussed in the following pages will create a more concrete understanding of the physics in rowing. These basic definitions will create the basis for comprehension of the forces that create boat speed.

The velocity of the boat is mostly determined by the forces acting on the oar. The most important and complex modeling of the oar is where the blade meets the water. Due to the turbulent nature of water understanding this interaction becomes a complex task. In addition, the blade slips in the water which adds another element that must be accounted for in the mathematical modeling of rowing. The combination of these two variables makes these equations near impossible to solve and computer simulations are often needed. However, with a more accurate models, new blade and boat designs can make rowing more efficient.

Efficiency is the key to success in most machines and it is no different in rowing. The oars and shell combine to create a highly efficient machine. It is in the complete understanding of their interaction with each other and the water where greater efficiency can be obtained. Precious tenths of a second can be gained by increasing the efficiency of the boat wherever possible which could lead to faster boats.

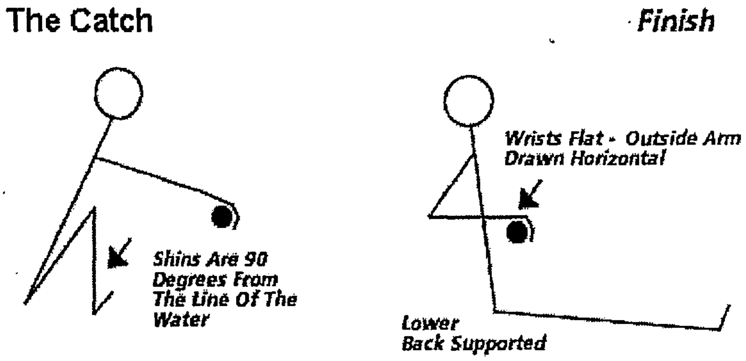
In the end, it is the prospect of beating other boats that propels the engineering behind rowing. The physics of rowing is hazy in places and several assumptions have arisen in the rowing community on how to build a faster crew. Similar to the corked bat in baseball, most of these ideas do not hold credence when tested. However, it is important for these anomalies to come forth and challenge orthodox assumptions to ensure that engineering remains at the cutting edge. By compiling several ideas proposed over the years, this comprehensive analysis will both show the evolution of rowing and its equipment and will shed light on why the orthodox beliefs have remained or crumbled under scrutiny.

Rowing is becoming an increasingly popular sport in the United States as colleges and universities invest more money into their programs. The growth of the sport has led to new interest among the scientific community to research the physics behind rowing and to make the boat go faster. Even when the biomechanical element is removed, the force, velocity, and other equations remain complicated and some still remain in question. The solution to these unknowns will not only benefit the rowing community but will lead to a better understanding of fluid mechanics and to the unusual type of vehicle propulsion that is rowing.

In Chapter 2, an explanation of the physics that propels the boat is explained. Chapter 3 gives a detailed explanation of the interaction between the blade and the water, the manufacturing of oars, and the ensuing testing of new designs. An in depth investigation of the efficiency of rowing and blades is given in Chapter 4. Chapter 5 targets four myths in the rowing world and provides a scientific analysis of their value. The conclusion is provided in Chapter 6. Appendix A provides some analysis of the properties of water and their effect on rowing performance.

Chapter 2: The Physics of Rowing

Rowing has been a Rubik's cube to engineers and physicists. The crew shell appears on the surface to be a simple machine made up of levers and fulcrums. It's not quite that simple. When rowing in a shell, a rower starts scrunched with knees bent as his/her blade catches the water he pushes back. This position is called the "catch" and illustrated in Figure 1a. As the rower pushes back, he initiates the effort with his legs pushing down on the footplate, just before the legs are fully pressed down he begins to bring his back over, and then contracts his arms. The whole movement is referred to as the "drive". The end of the drive culminates with the rower extracting the oar at the "finish" illustrated in Figure 1b. The rower then feathers the blade, reverses the movements of the drive and returns to the catch, in a phase called the "recovery". Therefore a rower is never stationary and the center of mass changes depending on his position, as well as the position of the other rowers in the boat. In addition, while the rower is moving, the oar is travelling in a paint splatter arc. Finally, the force acting on the blade is the reaction of a fluid which further complicates the equation.



Figures 1a and 1b

To better discern the forces during the drive and recovery physics equations are used to their full extent and experimental data supplements and/or confirms the theories. Methods for measuring force and qualifying equations include the use of strain gauges placed inside oarlocks which measure the force at the fulcrum and linear radio potentiometers that are placed in the oarlock to simultaneously measure the angle of the oar.

Another process for measuring force involves simulating and measuring flow over the blade of the oar. This is accomplished in a flow tank or with computer models using steady state flows. A problem with this path is that during rowing the flow of water over the blade is rarely constant. This inconsistency comes from several variables including: variations in angular momentum due to energy output from the rower; change in the oar angle through out the stroke which effects the direction of the pressure on the blade; and turbulence created on the surface of the blade. Macrossan [1] counters the aforementioned inconsistencies by stating that even though most tests are done with steady state flows, the change in pressure distribution will not dramatically change even though the velocity of the water at each point on the blade will. This is due to the curvature of the blade. The pressure will always increase towards the larger leading edge. Blade design is a cutting edge science and will be explored in Chapter 3. The momentum of the boat cannot be solely understood through an analysis of the oar blade. What now must be addressed is the movement of the boat created by the oar as a lever and the rower.

We consider Newton's law in relation to the motion of the boat. At rest, the momentum of the boat and water system is zero. While rowing, the total momentum of the system remains zero. The mass of the boat times the velocity of the shell, as viewed by an observer on shore, must be equal to the mass of the water moved times the velocity of the water propelled in the opposite direction from the boat by the oars. A basic equation that defines rowing is the energy equation. The kinetic energy during the stroke is defined as

$$U = 1/2 * m_b * v_b^2 + 1/2 * m_w * v_w^2 \qquad (1)$$

where m_b is the mass of the boat (with rigging, rowers, oars, and coxswain), v_b is the boat's mean velocity, m_w is the mass of water moved, and v_w is the velocity of the water moved. The energy produced by the rower must provide for the kinetic energy given above plus the energy lost due to the friction of the boat against the water. Ideally we would like to minimize the frictional losses and minimize the slippage loss due to the motion of the water. Thus most of the energy of rowing is channeled to the kinetic energy of the boat through the application of the oar to the water [2].

As defined by Fédération Internationale des Sociétés d'Aviron (FISA, rowing's international governing body), oars must be a class 2 lever where the water acts as the fulcrum, the oarlock acts as the load, and the rower supplies the effort. FISA's definition is from its belief that the oar remains stationary in the water. This categorization places oars into one classification when in fact, the type of lever an oar most accurately represents is dependent on the point of view of the person observing the action. By categorizing an oar as a class 2 lever, FISA makes equations longer and more difficult to solve.

Equations become simpler if the oar is defined as a class 1 lever where the end or blade of the oar supports the load, the oarlock acts as the fulcrum, and the effort is supplied by the rower. In the class 1 lever, the oarlock acting like the fulcrum helps simplify the equation due to the fact that it is a stationary, solid point of force when we use a frame of reference attached to the boat. These characteristics are contrary to the class 2 lever FISA defines where the fulcrum is the water, a moving, turbulent, liquid force. To understand the differences between the two classifications, the following equations are used.

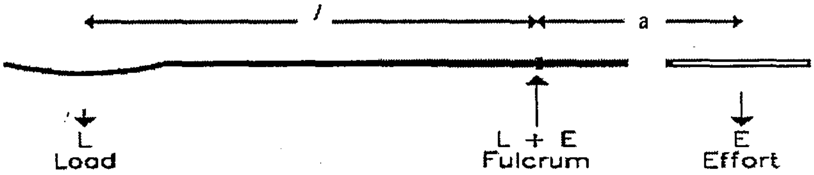


Figure 2: Type 1 Lever [2]

For a class 1 lever:

$$Load = Effort * (a / l) \qquad (2)$$

where *l* is the outboard length (from the oarlock to the blade) and "a" is the inboard length (from the oarlock to the end of the handle). This equation leads to the idea of gearing or the ratio of distance the load moves divided by the distance the effort side moves (i.e. the distance the blade moves/the distance the handle moves). The larger the ratio (value of *l*/a) the heavier the load feels to the rower. Manufacturers have made oars easily adjustable to suit rowers of varying sizes and abilities. For our calculations, we will assume that the oar is at optimal length [2].

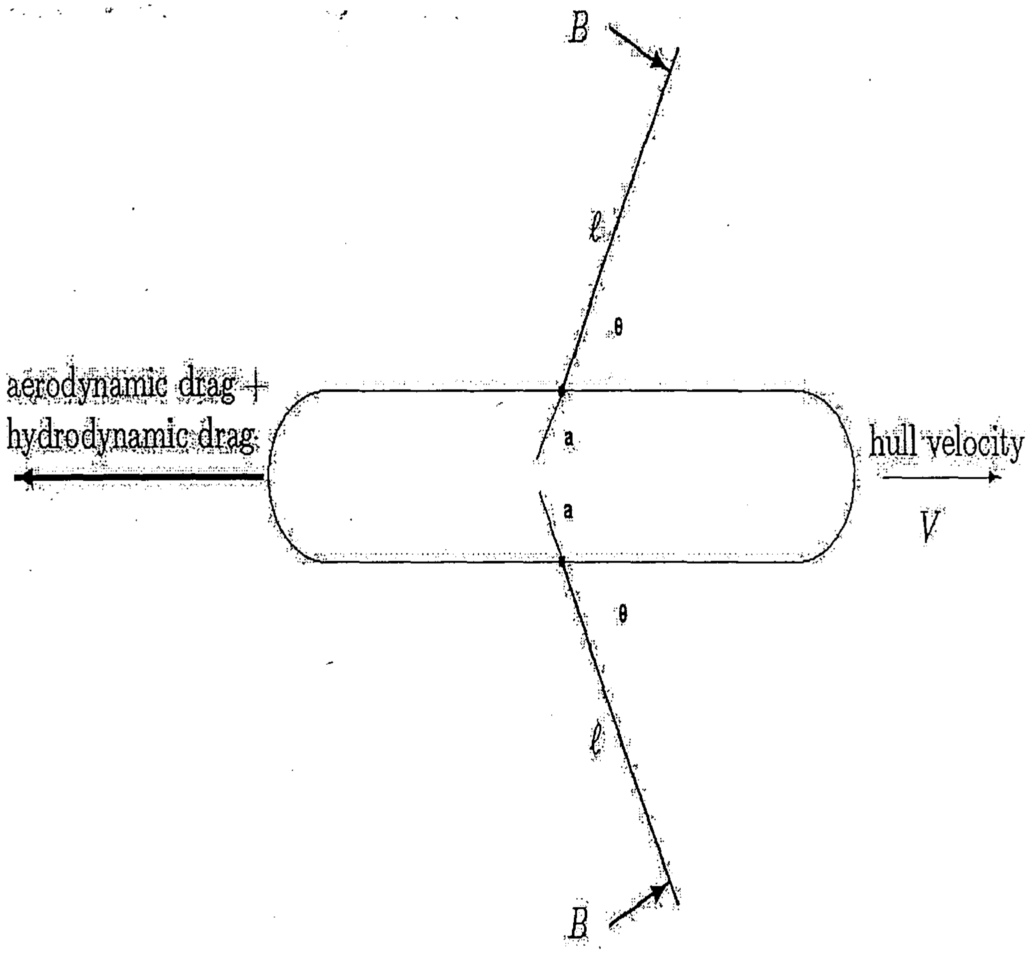


Figure 3: Basic Rowing Free Body Diagram (It should be noted that hulls are not shaped as ovals, this drawing just identifies the forces) [1]

The load on the oar comes from the water or Blade force (B) acting in the same direction as the velocity vector of the boat but opposite to that of the drag forces. The oar (rower) exerts a force more or less in the same direction. But as shown in the diagram of figure 4, the rower's force is parallel to the velocity direction but the load is perpendicular to the blade. The drag forces diminish the hull's velocity. Rowers must add energy at a sufficient rate over this dissipation to maintain speed.

In most studies, the blade force is considered to act perpendicular to the blade for simplicity. In reality, as the oar moves through the water, the blade force vector changes due to the fluctuations in pressure distribution. Only the component of the blade force acting parallel to the boat is useful in propelling the boat forward. The perpendicular component places a strain on the shell [3]. This component is canceled out due to what many observers have assumed to be an equal and opposite force coming from a blade force on the opposite side of the shell.

The force R, shown in the following picture, is the force applied on the oar by the boat at the oarlock. This force is directed opposite to the motion of the boat. However, it is the main reason for the motion of the boat. The reaction to the force shown, is a force applied by the oar on the boat which acts in the opposite direction and it is of the same magnitude.

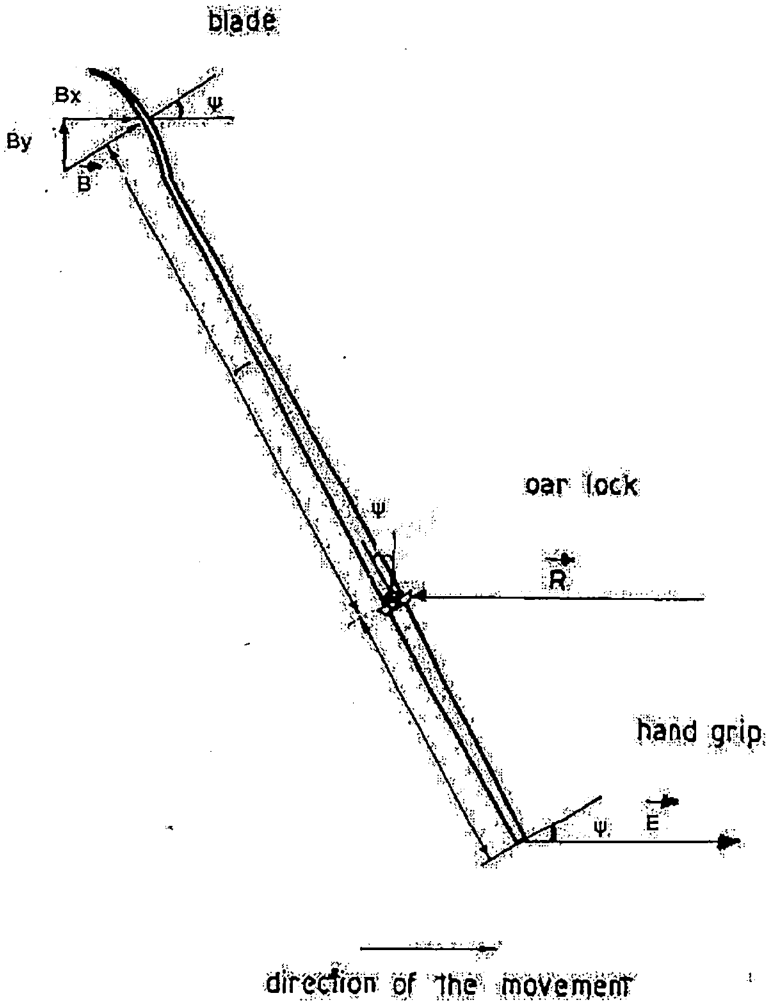
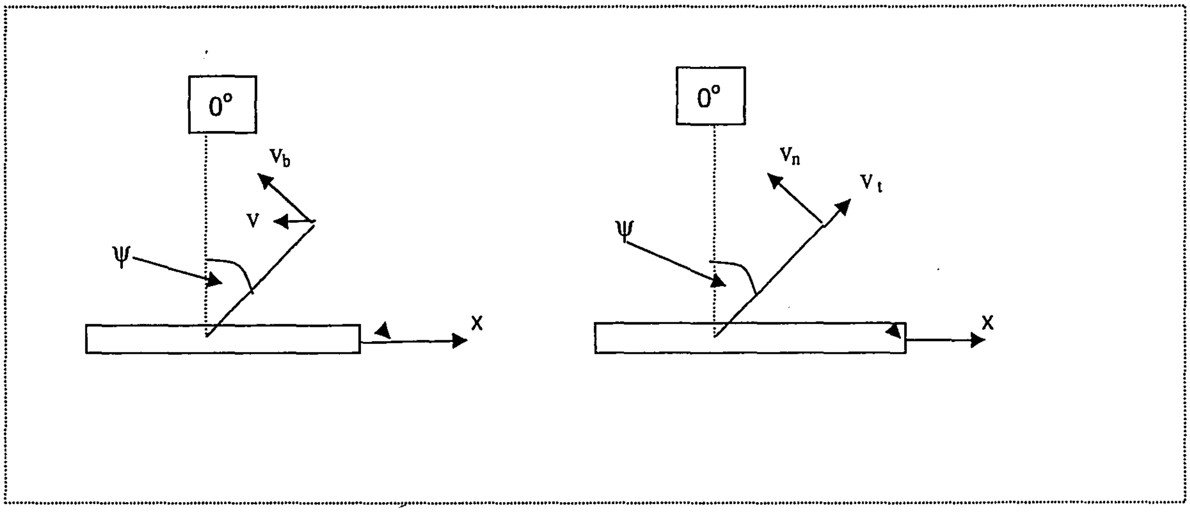


Figure 4: Rowing Free Body Diagram of the Forces on an Oar [2]

The velocity of the blade relative to a coordinate system attached to the boat is normal to the blade and equal to

$$v_b = \theta' * l \quad (3)$$

where θ' is the angular velocity of the oar. The velocity of the water relative to the coordinate system attached to the boat is parallel to the boat, equal to speed v of the boat but directed in the opposite direction as shown in the diagram 5. Consequently the normal and tangential components (see diagram 6) of the velocity of the blade relative to the water are given by



Diagrams 5 and 6: Velocity Components of the Blade

(x indicates the direction of the movement)

from the catch (where the oar is placed in the water) to mid drive (approximately 0° or normal to the boat) are

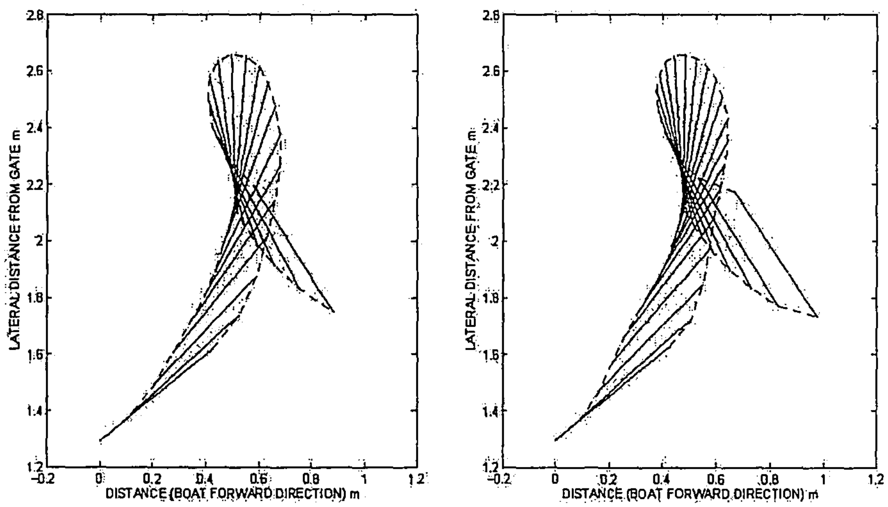
$$v_n = \theta' * l - v * \cos\psi \qquad (4)$$

$$v_t = v * \sin\psi \qquad (5)$$

where v_n is the velocity vector normal to the blade, v_t is the velocity vector transverse to the blade. Typical values of the oar angle, ψ, range from -40° to 60° where 0° is perpendicular to the boat. The angle of attack α, or the angle between the chord line of the blade and the blade velocity vector, is defined as

$$\alpha = \tan^{-1}(-v_n / v_t) \qquad (6).$$

Determining the force components and the angle of attack is difficult once the oar passes 90°. This is because the oar blade does not travel in an arc but it travels in a small loop similar to the shape of a script lower case “l”. At the end of this path, the blade starts moving through water it already set in motion. This also makes determining the oar velocity relative to the water difficult since it is hard to know the velocity of the moved water at that point [1]. Figure 5 defines this motion with the x-axis depicting the distance the oar moves in the direction of the boat's velocity and the y-axis depicting the distance of the blade from the gunwales.



28.1 strokes/min

40.8 strokes/min

Figure 7: Actual Motion of the Blade at Various Stroke Rates (The stroke starts at the left part of the graph).

In examining Figure 7, it is seen that the blade, when viewed from a fixed coordinate system, moves forward together with the boat and the rowers in the x direction while at the same time rotating and getting farther from the boat in the y direction. If the top broken line is followed from the start of the stroke (i.e. the motion of the near end of the blade), it can be seen that the blade moves smoothly forward until we reach the zero angle. Then at negative angles the motion forward continues as shown by the lower broken line of the figures towards the end of the stroke. Of course, the rower views the motion of the blade from a coordinate attached to the boat, thus the blade appears to follow a circular arc.

In order for the oar to move (both during the drive and recovery), the rower must supply enough force so the torque acting about the inside of the oarlock is greater than that provided by the blade force to the outside [3] . Thus in view of figure 4, we have

$$E * a * \cos\alpha \geq B * l \quad (7)$$

Our formulation up to this point followed the simple and idealized situation. However several factors complicate the analysis. For example, force and velocity are not constant in rowing but oscillatory. This is due to the oar being extracted from the water and drag causing the boat to decelerate. The boat's velocity oscillates around the mean velocity. This oscillation or pulsing can be modeled by the impulse theorem given as

$$-n * \int_{t_1}^{t_2} Rs\, dt = m\left(v_f - v_0\right), \quad (8)$$

where t1 and t2 are the start and end times of the oars being extracted, n is the number of strokes, Rs is the sum of the resistance hydrodynamic and aerodynamic forces, v_f is the maximum velocity of the boat, and v_0 is the minimum velocity. However, values must be corrected for the mass of the moving oarsman. This is due to the rower driving faster than the movement of the shell in respect to the water. The energy generated aids the rower's acceleration. The same idea follows during the recovery and deceleration. The momentum back and forth lessens the speed of oscillations/pulses.

The relationship between rowers' movements and the velocity of the shell during both drive and recovery are not completely understood because most studies did not take the rower's momentum into account in their calculations. These studies assumed that rower's mass had no affect on the overall momentum of the boat. This resulted in the assumption that the rower was a stationary mass in the equations studied.

On-water studies revealed that during the drive, body movements actually slow the boat. At the beginning of the drive, the rower generates energy to move the oar through his feet. The feet push off a footplate affixed to the boat. This force pushes the boat in the direction opposite to its momentum, and thus slows it down. Acceleration only occurs as the oar forces overcome drag forces and continue until the knees contract during the recovery even though the rower is not placing any exertion on the oar handle. Once the legs start contracting and returning to the catch, its momentum starts to decelerate. At this point, resistive forces take over and the boat begins to slow. Figure 8, which was obtained from experimental data, proves that the rowers' movements must be taken into account when modeling velocity in rowing. If the mass were stationary the drive would be a linear plot with a positive slope, and at the moment the blade was extracted from the water, the recovery would be modeled by a linear plot with a negative slope. (see below) [5].

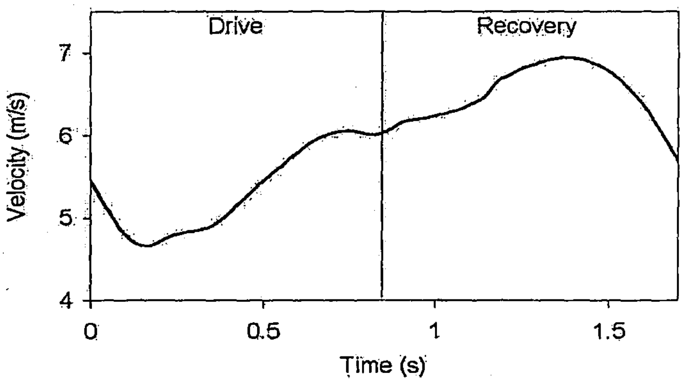


Figure 8: Velocity of the Shell Over Time

This contradicted many older models which assumed that the rowers were stationary with respect to the boat. These models showed a constant decrease in speed on the recovery since no force acted against the resistance.

Caplan and Gardner [5] tried to model the influence of crew movement on the boat's velocity. They considered the total momentum equation as

$$P - D = m * dv_{shell} / dt + M(dv_{shell} / dt + dv_{crew} / dt) \quad (9)$$

Where m is the mass of shell and accessories, M is the combined mass of the crew, v_{shell} is the velocity of the boat, v_{crew} is the velocity of the rowers relative to the boat, P is the propulsive force and D is the drag force.

By rewriting the above equations as

$$dv_{shell} / dt = (P - D - M * dv_{crew} / dt)/(m + M) \quad (10)$$

this equation illustrates that the crew acceleration relative to the boat may affect the acceleration of the boat. In order to estimate this effect, a five segment kinematic model was used [5] which consists of the shank, thigh, trunk, arm, and forearm. The centers of mass of these segments can be expressed in terms of the measurable coordinates of the knee, elbow, hip, shoulder, and hand. For this, one needs anthropometric data. The same data is also used to establish the relative masses of each segment. Consequently, one can estimate the products of mass time acceleration (i.e. force) for each segment. For example, for the shank the following equation applies

$$F_{shank} = 0.0465 * m(d^2 C_{shank} / dt^2) \quad (11)$$

where C_{shank} are the coordinates of the center of mass of the shank.

By combining all parts of the body, the equation becomes

$$F_{crew} = 2F_{shank} + 2F_{thigh} + F_{trunk} + 2F_{arm} + 2F_{forearm} \quad (12)$$

and the acceleration equation becomes

$$dv_{shell} / dt = (P - D - F_{crew}) / (m + M) \quad (13)$$

The main force battling the rowers' efforts to move the boat forward is drag. Drag on the boat occurs due to the transfer of energy from the boat to the water and air. Simply put, as the boat slows down, the surrounding fluids are accelerating. There are three types of drag in rowing: skin, form/turbulence, and wave (energy lost in the creation of waves by the oars and hull). Skin drag is defined as

$$D = a_1 * v^2 \qquad (14)$$

where a_1 is the constant dependent on the hull shape and surface. The constant, a_1, has been determined through empirical studies. The hydrodynamic force acts in the horizontal plane to the boat against the blade. Water opposes the blade in the same direction as the shell movement which is in opposition to the drag on the boat from aerodynamic and hydrodynamic forces. [1] Resistance to the progression of the boat is a non-linear equation related directly to how fast the boat is traveling. Thus, more momentum equates to a much greater resistance force. The total resistance force is modeled by the equation:

$$R = k * v^a \qquad (15)$$

where k and the exponent a' are constants with experimental values of about 5.0 and 1.8 respectively according to Celentano et. al. [3]

Up to this point, the focus has been on the forces acting on the boat and how they can result in its acceleration or in its constant speed of motion. An alternative view is the discussion of the energy balance. The water resistance depletes the energy of the system. If a constant kinetic energy is to be maintained, i.e. constant boat speed, then the rowers must supply the equivalent work through the oar during the drive. The power (work per unit time) supplied by the rowers can be written as

$$P = W * f \qquad (16)$$

where W is the work done per stroke and *f* is the frequency of the strokes.

Some researchers utilize the following equation to describe the work done by each rower

$$W_{man} = B * (v * s_{boat} + r) \qquad (17)$$

hence B is a constant, v is the boat speed, s_{boat} is the displacement of the boat and Br represents the energy lost due to the blade movement, heat, and turbulence.

Run	Athlete	Strokes/min (f)	No. of Strokes Counted for Calculation of W	Distance Traveled with No. of Strokes, m	Mean Speed (v_m), m/s	Work/100 m (W), J	Negative* Work/100 m, J	Work*/Stroke (W), J	Speed Oscillation, ΔV%
4—5	Mu●	24.4	11	97.6	3.61	6550	920		
6—7		29.7	13	101.6	3.87	6040	2020		
8—9		36.3	15	99.8	4.03	7760	2000		
10—11		38.1	15	97.1	4.11	7820	2120		
35	*Sp* ○	289	12	998.5	3.95	7250	0	595	7.4
36		21.2	12	102.4	3.01	4590	0	392	16.6
37		37.6	14	100.5	4.5	8820	0	633	3.8
40	*Fe* △	24.5	12	101.4	3.45	5340	0	451	11.1
42		36.7	15	102.1	4.16	8580	0	584	4.3
43	*Or* □	21.9	10	97.5	3.56	3810	0		
44		27	12	98.2	3.68	6400	0		
45		36	14	97.1	4.17	6980	0		

* *For one oar only.*

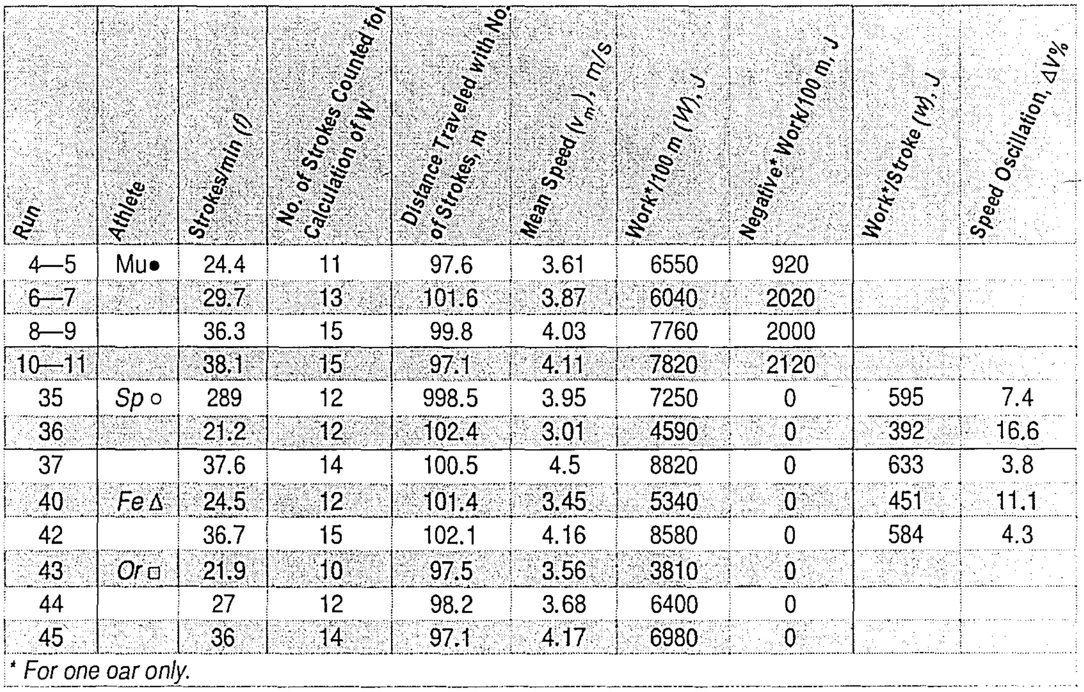
Table 1: Experimental Data for Various Rowers (Note Negative Work Column) [3]

Table 1 is experimental data obtained by Cortili, Prampero, and Cerretelli [3]. This table shows the amount of work done by various rowers of different abilities at various stroke rates. This data was used to validate Equation (15) provided above for work done by rowers. Note the negative work performed by rower "Mu". This is due to the rower's lack of disciplined technique placing the oar in the water. Since the oar was

Some researchers utilize the following equation to describe the work done by each rower

$$W_{man} = B * (v * s_{boat} + r) \qquad (17)$$

hence B is a constant, v is the boat speed, s_{boat} is the displacement of the boat and Br represents the energy lost due to the blade movement, heat, and turbulence.



Run	Athlete	Strokes/min (f)	No. of Strokes Counted for Calculation of W	Distance Traveled with No. of Strokes, m	Mean Speed (v_m), m/s	Work*/100 m (W), J	Negative* Work/100 m, J	Work*/Stroke (W), J	Speed Oscillation, ΔV%
4—5	Mu●	24.4	11	97.6	3.61	6550	920		
6—7		29.7	13	101.6	3.87	6040	2020		
8—9		36.3	15	99.8	4.03	7760	2000		
10—11		38.1	15	97.1	4.11	7820	2120		
35	Sp ○	289	12	998.5	3.95	7250	0	595	7.4
36		21.2	12	102.4	3.01	4590	0	392	16.6
37		37.6	14	100.5	4.5	8820	0	633	3.8
40	Fe △	24.5	12	101.4	3.45	5340	0	451	11.1
42		36.7	15	102.1	4.16	8580	0	584	4.3
43	Or □	21.9	10	97.5	3.56	3810	0		
44		27	12	98.2	3.68	6400	0		
45		36	14	97.1	4.17	6980	0		

* For one oar only.

Table 1: Experimental Data for Various Rowers (Note Negative Work Column) [3]

Table 1 is experimental data obtained by Cortili, Prampero, and Cerretelli [3]. This table shows the amount of work done by various rowers of different abilities at various stroke rates. This data was used to validate Equation (15) provided above for work done by rowers. Note the negative work performed by rower "Mu". This is due to the rower's lack of disciplined technique placing the oar in the water. Since the oar was placed in the water slower than the boat, the blade acts as a break and reduces the velocity of the shell.

At any stroke rate, the work performed by the rower during each drive is equal to the work done by the blade force. This is because there is no displacement of the resistance at the oarlock is zero to an observer in the shell. The oarlock force is determined to be zero because the rigger/oarlock does not move in the x direction relative to the boat (side note: it has been determined that sliding riggers that do move in the x-direction are faster than traditional rowing methods. However, both FISA and USRA rowing rules have banned these devices causing the crew shell to remain unchanged in this respect [3].

During the initial phase of the stroke, or catch, the force of the blade force is directed slightly inward and thus is not completely counter acted by the oarlock. Thus, rowers should not spend too much time at the catch or initiate the drive with too much energy (i.e. commonly referred and encouraged as "jumping off the foot stretchers") because the energy generated (propulsive force) will be wasted and actually absorbed by the rower and their blades. The actual energy or propulsive force to be transferred from the blade to the rower is completely dependent on oar angle and is defined by the ratio B/E. During the most effective part of the drive (when the oar is just past perpendicular to the boat, $\alpha = 16^{o}$), this value is approximately 0.11. Experimental results reveal a significant deviance from those predicted (~ 50% error) for elite athletes and much higher for lesser trained rowers.

The most compelling explanation for the significant deviance is that the blade force is not constant in direction or intensity during the drive. These inconsistencies will have the greatest impact on the results since the mathematical equations work with the assumption that the force is constant. In addition, the assumption that the rower applies all the effort to the oar handle parallel to the shell is incorrect. There is actually a force vector outward towards the oarlock. This results in the greater the inclination towards the oarlock the greater the discrepancy in the ratio. As little as a 5° inclination results in a doubling of the ratio. This inclination is related to the inboard length of the oar and must be adjusted to suit each rower's physical characteristics. [3]

Chapter 3: Blade Work

3a: Blade Theory

Rowing is an ancient sport dating back to the days of the Egyptians. One can find hieroglyphics that show oared boats moving up and down the Nile. Back then, oars were cumbersome, wooden logs that required more than one slave enduring back breaking work to handle. Rowing became a sport around the time of the America's Civil War. Merchants would race to see who could transport their goods and passengers up and down rivers the fastest. Common sense told these merchants that a more efficient propulsion device would give them an edge on their competitors. **Figure 9** shows one of the earliest patents for oar design.

To break down rowing even further, it is the part of the oar that comes in contact with the water that is most important to propulsion. This is because the blade has the most resistive forces acting on it and, due to gearing, offers the most force to overcome this resistance. The forces acting on the blade were briefly talked about in the last chapter.

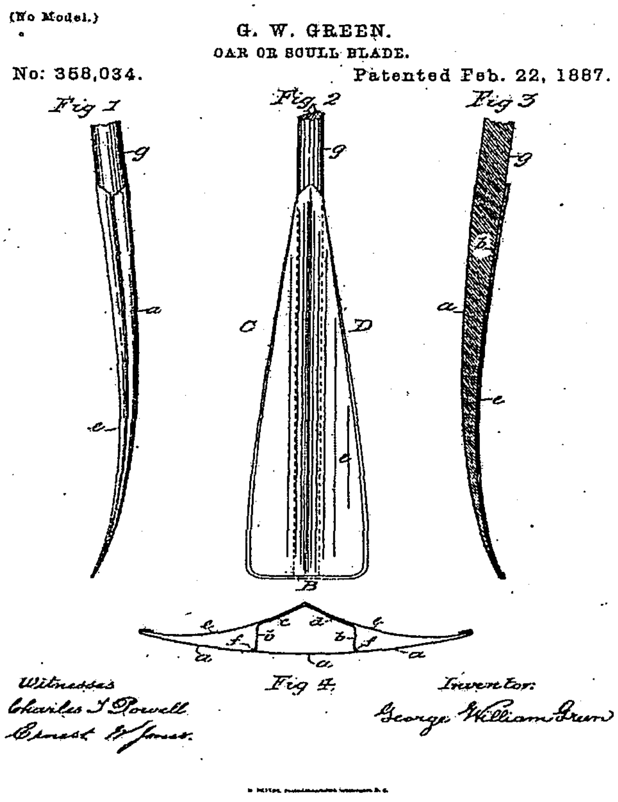


Figure 9 (Courtesy U.S. Patents Office)

Before designing an oar, it is important to define how the blade acts in the water. Manufacturers and engineers have assumed for years that the blade acts similarly to that of an airplane wing. Scientific, academic, and scholarly papers often refer to the blades' angles of attack, lift, and stalling. Stalling occurs when the critical angle of attack is exceeded. The critical angle of attack is the angle at which the blade or wing generates significant turbulence off the trailing edge. This turbulence causes the pressure differential between the two sides of the foil to lessen. The high pressure on the front applied by the water leaves a low pressure, almost a vacuum effect, on the back side of the blade. This differential causes the blade to lift. Drag on the blade comes from this pressure differential as well as from the water flowing over the blade's surface.

During low angles of the stroke, shear friction builds to its greatest level on the blade and this friction will act on both the fore and aft sides of the blade. This shear friction causes the boundary layer flow to become turbulent [1]. Figure 10 shows the fluid flow over an airfoil at different angles of attack. As the angle of attack increases, so does the turbulence off the trailing edge.

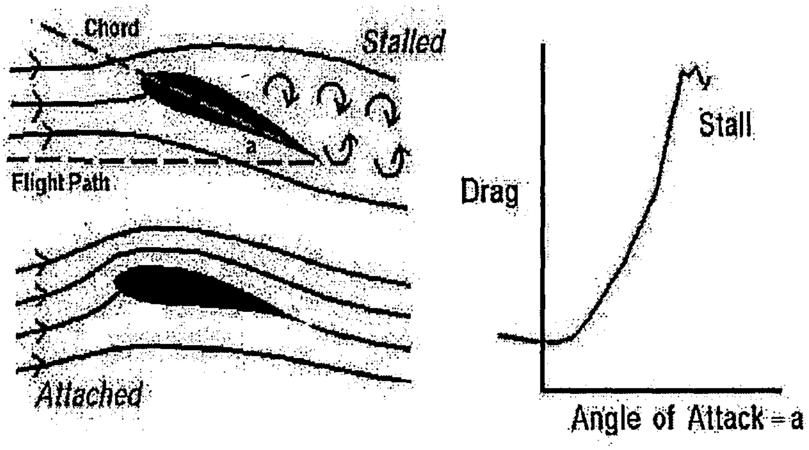


Figure 10: Diagram Explanation of Stalling [7]

However, Macrossan [1] argues that blades do not act identically to airfoils. Both parallel and normal force coefficients are much greater in an airfoil than that of a hatchet blade (with the parallel forces of an airfoil being about ten times greater). In addition, a sculling blade stalls at an angle of attack of approximately 10° while an airfoil stalls at about 16°. Macrossan explains this phenomenon. He states that the tangential force is larger due to the asymmetrical loading of oar blades. The pressure away from the oar lock acts on a greater area than that of the water acting inward. This is due to the larger area of the blade being at the leading edge rather than at the trailing edge. This conclusion would be true even if the forces are equal across the face and back side of the oar. Macrossan confirmed this trend by comparing blades with different surface area distributions. The airfoil comparison also loses some credibility due to the fact that an efficient blade hardly moves while immersed in the water while the wing of an aircraft does move through the air. [1]

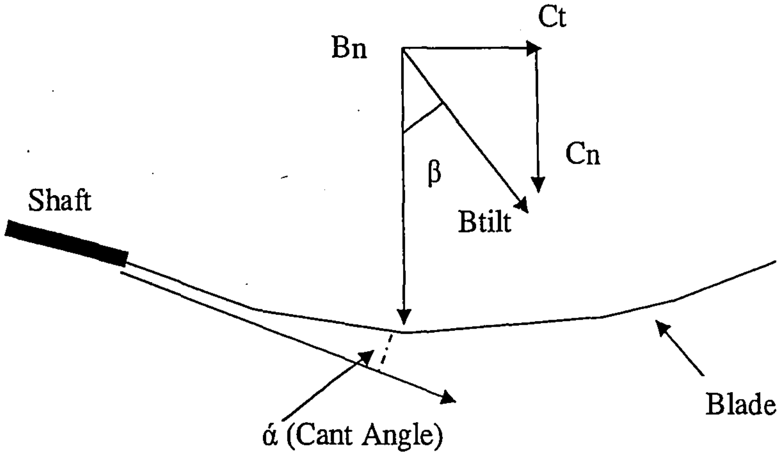


Figure 11: Tilt Angle and Cant Angle Defined

A good parameter that has been used to compare the blade and airfoil is called tilt. Tilt is a postulated angle since it is too small to be correctly measured. The idea of tilt is this: The design of the blade may cause the blade force Bn generated by water pressure to tilt and actually act in a direction Btilt forming an angle β with the perpendicular to the cord line (see figure 11). The normal and tangential components of Btilt are denoted by Ct and Cn as shown in the figure. The tilt angle beta is thus defined by

$$\beta = \tan^{-1}(Ct/Cn) \quad (18)$$

By using Equation (18), tilt can help predict when a blade will begin to stall. Stall occurs just after the tilt reaches a maximum when plotted against the angle of attack. **Figure 12** compares the tilt of a typical airfoil and the Concept 2 Big Blade.

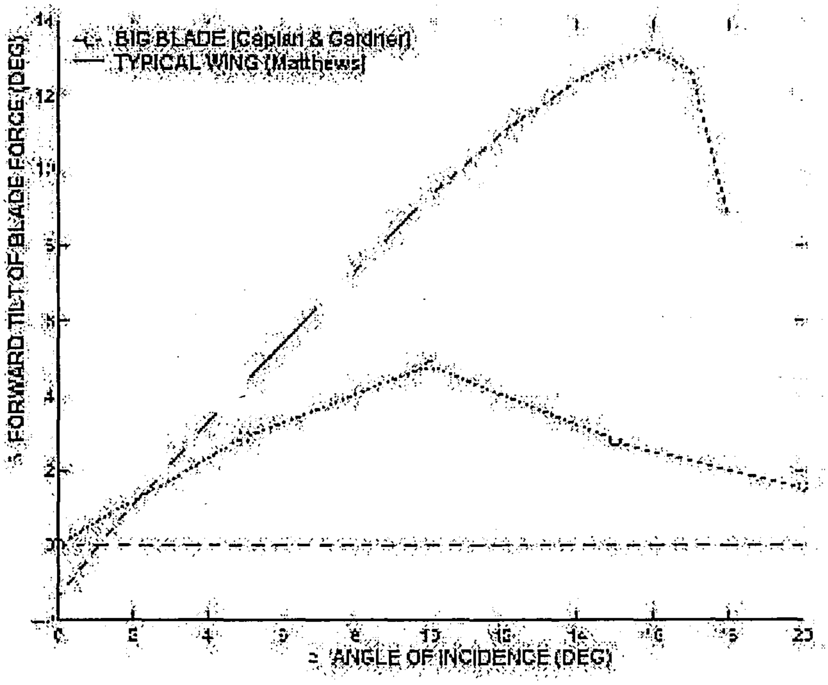


Figure 12: Comparison of Tilt Angle for a Rowing Blade and an Airfoil [1]

Figure 12 reveals that there is a similar trend between the two foils. The large values of tilt associated with the airfoil are a direct result of the large symmetrical pressure differential along the surface of the wing. It had been argued that rowing blades share a similar profile with less magnitude due to the same non-uniform pressure differential but with different force coefficients. However, the forward tilt of the blade force does not drop as significantly after the stalling point due to the increase in turbulence causing a loss in pressure differential and thus a loss in lift.

The turbulence generated on the blade results in another problem: Slippage. Slippage is the distance the oar moves in the water, from the stationary observer's point of view, and the amount of water displaced. A perfect blade would result in no water moving backwards. A good example of how a perfect blade would move: simply drop the blade in the water and apply no effort to the oar handle while the shell moves. The oar at this point is as close to a zero slip blade (slippage) as possible and would remain almost still as the boat passed its position in the water.

The blade will follow the path of least resistance or the path with zero lift. This path is called a tractrix, or the curved path the oar moves influenced by friction and moved by the water at a nominal speed. Since the oar has a given cant angle or angle the blade makes with the shaft (see Figure 10), it follows the path of an oblique tractrix. As the rower adds energy to the handle, the blade begins to slip more and deviates from the zero slip tractrix. As the rower nears the finish and his power decreases, the blade returns to the zero slip tractrix. It should be noted that slippage does not diminish the propulsive force from the rower [5]. However, the lack of inertia on the blade can cause the rower to lose control of the blade. When that happens, the boat slows.

Describing the motion of the oar blade is more difficult and confusing. Why? It all depends on whom one relies for information. To the rower, the oar moves about the boat in an arc. This is an optical illusion. The rower feels as if he is moving the oar through the water but it is the oar that is almost stationary as the boat moves past the blade. Beaton [8] gives a more accurate description based on slow motion photography taken from a bridge as a scull passed underneath. The blade moves both laterally and slightly backward throughout the stroke. This movement is minimal compared to the movement of the boat. It has been suggested that the lateral movement of the blade is the dominant velocity vector through 95% of the stroke. The 5% of the stroke left over is where the oar is normal to the boat. During the majority of the stroke, lift contributes to the velocity of the boat (at points when the oar is not normal to the boat). When the blade is perpendicular to the boat, drag forces are responsible for the velocity vector [8].

Using the same approach as Beaton, Concept 2, a major oar manufacturer in North America, states that there are four phases of blade motion. In phase one, the movement of the blade is towards the finish line because of the shell's momentum. Next the blade moves perpendicularly away from the boat due to the rigging pushing the oar as the boat passes the blade's pivot point in the water. During phase three, the blade travels towards the start or stern of the boat due to oar slipping in the water. Finally, the oar moves inward towards the gunwale of the boat [7].

These movements in combination with the flow of the water over the surface of the blade all contribute or detract from the movement of the shell. Concept 2 refers to the pressure acting on the blade as the loading profile. The loading profile is how "heavy" the oar feels to the oarsman during the drive. The profile is directly related to how fast the rower can move the handle at various intervals of the stroke. The difference between different blade designs becomes more apparent at sharper catch and finish angles. This is because the blade forces at the early and late part of the stroke act on the oar at extreme angles. The shape of the blade changes the pressure differential between the front and back of the blade. Figure 13 details the loading profile of Concept 2's available blade designs [7].

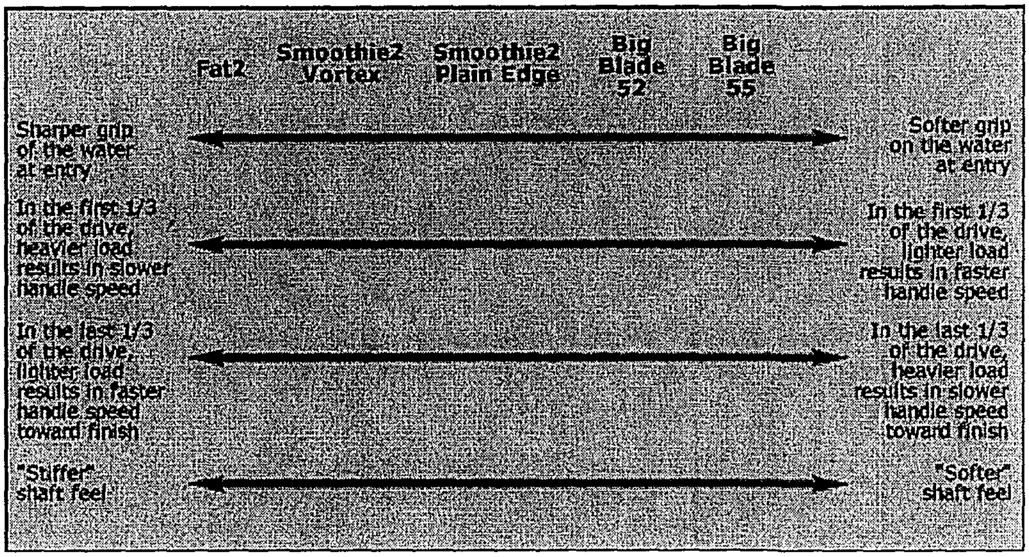


Figure 13: Loading Profile of Various Concept 2 Blade Designs

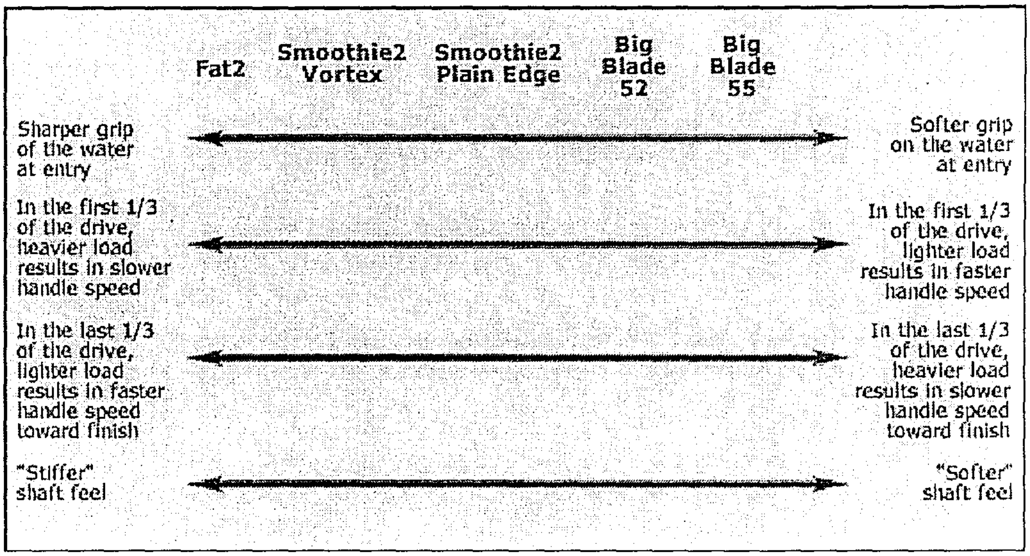


Figure 13: Loading Profile of Various Concept 2 Blade Designs

SubChapter 3b: Blade Manufacturing

Understanding all this information is only theoretical unless a manufacturer has the technology and materials to produce the optimal product. Up until the 1980's oars were made up of small strips of wood laminated together. These oars were heavy, difficult to use, and had limited shape capability. They also had a relatively large curve and a spline where the oar shaft intersected with the blade. Light reinforced plastics and fiberglass designs replaced wood blades but not the shaft. Now oars are entirely made of composite materials. While the materials transferred from wood to fiberglass to carbon composites, the design remained unchanged. As the more easily molded composites became available, more advanced oar shapes were developed such as the Concept 2 Big Blade and the Dreher Flat Blade, more commonly known as hatchets.

Composite oars are made up of a constituent and two or more reinforcing materials which add strength to the matrix of the constituent. Here the fibers carry the load (blade force) and strength is related to the volume fraction of the composite and the orientation of the fibers. [9]

Oar use falls under Basquin's law for cyclical loading because of the changes in stress during the drive and recovery phase as well as the changes in water pressure during the drive.

$$\Delta\sigma N^a = C_1 \quad (19)$$

Where N is the number of cycles to failure, $\Delta\sigma$ is the bending stress range (here dependent on the force the rower places on the oar), a is constant between 1/8 and 1/15, and C_1 is a constant based on a low or high fatigue cycle. Blades are also subject to shear and torsional bending. The material used must be able to withstand these forces while simultaneously transferring the rower's power to the velocity of the shell [9].

Several processes are currently used for making blades. Contact molding has been used for many years. In this process, a laminate is placed on a mold coated with a release agent. Resin is then applied. The resin covered laminate is then cured in an oven or autoclave. The part is removed and then it is trimmed, polished, and finished. The lay up process for contact molding has become automated in which a machine sprays the resin and laminate fibers at once into the mold. This has offered a faster and more uniform product but it is more expensive. Other advances in this process include the use of prepregs and vacuum bagging (placing a bag over the mold, attaching a vacuum and removing the excess resin out of the mold). Both advances eliminate excess resin making the oars lighter and stronger [9].

Another process used in oar manufacturing is press molding. This process can either be done hot (cured in an oven) or cold (cured at room temperature). Both processes use a slurry containing fibers and binders. The slurry is placed in molds, pressed, and cured. Cold press molding occurs in about ten minutes while hot press molding takes a few hours. In order to have a more uniform cure, sensors have been developed. They are placed in the slurry and on the molds where they monitor temperature and heat flow through the molding process. This data reveals inconsistencies in the mold and through trial and error of mold design the process can be near perfected [9].

The shaft of the oar is manufactured by a different, highly innovative process called filament winding. Here a fiber feeder adds strands of prepreg around a mandrel. There are three different types of filament winding. The helical method is where the mandrel rotates in position and the fiber feeder adds material by moving left and right. In the polar method, the feeder moves tangentially back and forth to the mandrel. The hoop method is where the fibers are wound helically at a 90° angle.

Subchapter 3c: Blade Design

In the 1960's, the macon or spoon design was created. These oar blades resembled spoons or tulips as seen in Figure 14. This design was stout enough to last until the late 1980's when the hatchet blades (see Figure 15) were introduced by Concept 2. Although hatchets are the most popular choice some traditionalists still row with the macon blades. Most rowers believe that the hatchets are faster but there is little evidence to support this theory (to be discussed later).

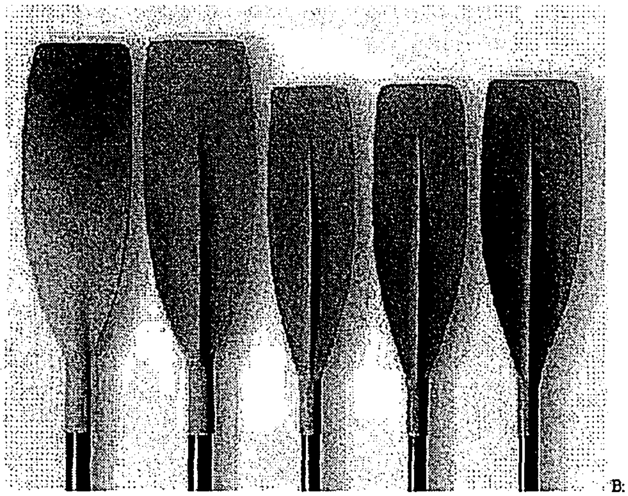


Figure 14: Macon Blades (Sweep Blades on the Left, Sculling to the Right) [9]

The manufacturing leaps forward in the use of synthetic materials offered more possibilities than that of the wood laminates. This is due to composites' strength at relatively thin thicknesses and elaborate bends. Concept 2's synthetic macon oars were lighter and stronger than the previous wooden oars. Also the synthetics provided a variety of flexes in the oar shaft to be offered to rowers of varying abilities, and physical stature.

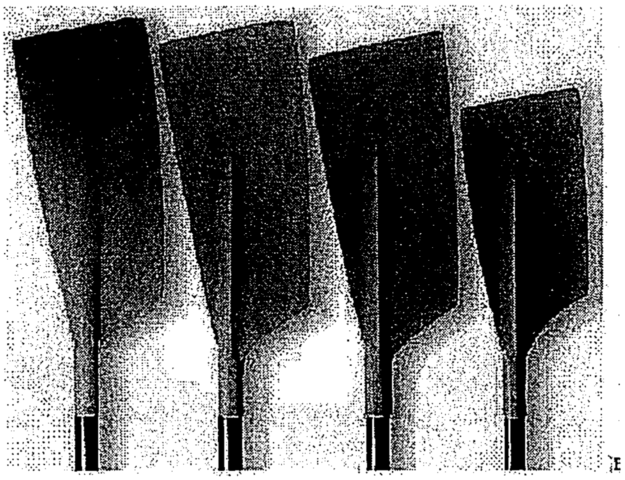


Figure 15: Hatchet Oars [9]

After Concept 2 offered its new-synthetic macon oar to the market in 1989, Bob and Jim Dreher, and Olympic medal winning team, saw some room for improvement. While using the oars, the brothers noticed the difficulty of oar extraction, severe pitch (angle the oarlock is to the water) sensitivity, and the diving of the blade during the end of the drive phase. While using the oars, Dreher noticed deficiencies in the Concept 2 design. These included difficulty oar extraction, severe oarlock and pitch sensitivity, and the blade tended to dive during the end of the drive [10].

Concept 2's sweep blades were made by taking a polyvinyl chloride (PVC) foam board center laminated with composite glass and carbon and epoxy skins. This was economical and manufacturer friendly but severely limited their design capabilities. Concept 2 also used a similar but smaller mold to create their sculls. The combination of the two is where Drehers felt the problem stemmed. They formed a company and called it Dreher [10]. Dreher is now one of the leading oar manufacturers in North America and Concept 2's biggest competitor.

This new company responded with a blade that was flatter but had more surface area and a rounded bottom. In addition, Dreher changed the manufacturing process. Its oars are individually molded foam and carbon composites. This process is capable of making complex three dimensional shapes. This process was considered such an improvement that Concept 2 eventually switched to it [10].

After testing its new design, Dreher claimed that its blades were 10% better than Concept 2's. At first the rowing community scoffed at the new design, but acceptance grew as its oars were part of more and more competitive crew's equipment at the national level. Crews changed oar designs as more rowers experimented with them and found the new design easier to handle. How much more force these newly designed oars transferred to the boat is unclear but the rowers had an easier time handling the oars properly during the stroke which made the difference at the finish line [10].

The narrowness of its scull and small size of its sweep oar blades led Concept 2 to release the Big Blade in 1991. This was the first time hatchet oars were introduced to the rowing community. Also known as clever blades, hatchets are shaped large and rectangularly. The shaft mates with the blade at the top of the blade versus the middle as was done with the macons. The theory behind this design was to put more of the blade's surface area in the water without the disturbance and resistance created by the shaft. This design also eliminated the amount of the oar shaft that was in the water making the blade easier to insert and extract. The Big Blade design added as much as 20% more surface area to the sweep blades. Concept 2 also snubbed the leading edge of the oar and added this to the width which created a more stable blade [10].

Dreher claims that the Concept 2's new oars were no more efficient or easier to control than the macon blades they were producing at the time. However, Big Blades began dominating the market at all levels and macon oars beagan to disappear especially on the competitive circuit. Despite the failing popularity of the macon blade design, Dreher pointed out that Italy won the light weight quadruple scull world championship in 1992 using macon blades [10].

Even with its avid denial of the new Concept 2 design, Dreher was not to be outdone. Dreher noticed that Concept 2 had decreased the extraction problems at the finish and created a more stable blade by decreasing its curvature. In an attempt to improve upon the advances made by Concept 2, Dreher test drove a new perfectly flat blade. This blade had almost no hitches at the finish but went too deep during the drive due to the lack of buoyancy. Dreher also noticed that the new design increased turbulence off the bow side of the blade. A new idea emerged that was a compromise between the two ideas. By increasing the spline or ridge incurred at the oar shaft to blade intersection, Dreher could increase the buoyancy of the blade. In addition, the lines of curvature are now in line with the flow of water which provides more lift at the catch. More lift at the catch starts the blade at the proper depth during the start of the drive. This makes it easier for the rower to keep the oar blade at the proper depth throughout the stroke, providing easier extraction at the finish and keeping the shaft out of the water which reduces drag [10].

As the competition in the rowing community grew, so did the competition amongst companies to build a more efficient blade. In 1998, Dreher released their LS1999 sculling blade. This hybrid design combined the shape of a macon blade with the surface area and shortened length of the Concept 2 Big Blade. The end result was a blade that was slightly smaller in width and area than the Big Blade. This idea came from an international customer and distributor who asked for a slightly smaller blade. His customers sang the praises of the LS1999 oar being easier to handle and they believed it performed better. Oddly enough, this design is similar to that of the tulips that were used in the 1960s but were made of composites versus the heavy wood laminates. After field testing, Dreher found that the performance and resulting speed generated by the LS1999 were equal to that of the Concept 2 design but they stated that the LS1999 entered and left water easier [11].

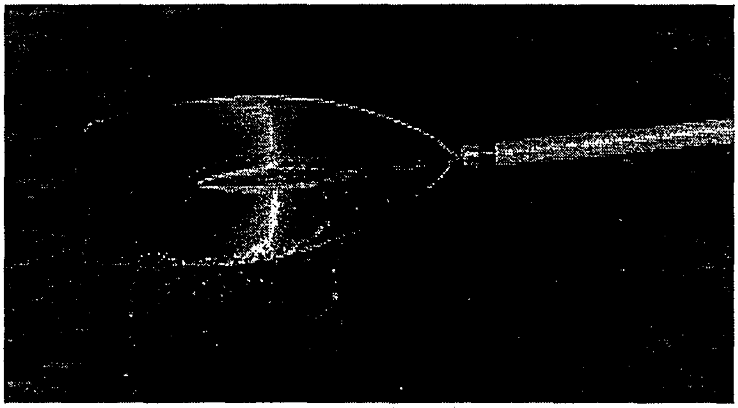
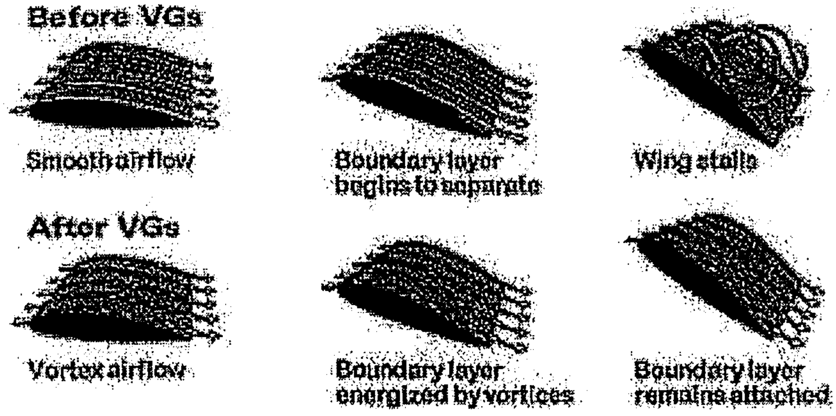


Figure 16: Dreher's LS1999 (Courtesy of www.durhamboats.com)

Concept 2 took the next step to creating the perfect oar blade when they released their Concept 2 smoothies. This blade is flatter than the traditional big blade and has a smooth surface with no spline (hence the name). In addition to the surface, the blades taper at the leading edge. The claim here is that the vortices will be generated along the edge of the blade. Testing revealed cleaner catches and finishes and less slippage during the drive [11].

Concept 2 then took the next step by adding a "vortex" edge to the leading edge of the oar in its release of the Smoothie2 Vortex. The "vortex" edge is simply a piece of plastic grooved with plastic teeth that covers the tip of the blade. Concept 2 claims that this piece of plastic acts similar to the vortex edges on the wings of planes in that it sheds the vortices off and away from the end of the foil delaying stalling and a loss of lift. This is most apparent at the beginning of the stroke. The edge creates a loading profile where the oar feels heavier during the catch and lighter towards the finish [7].



Concept II Website

Figure 17: Concept 2's Vortex Generators (VGs) [7]

Dreher's newest and most dramatic change can be seen in the Apex sweep and sculling blades released in late 1999. These blades were designed in response to the Concept 2 smoothies, although Dreher claims there was no advantage to rowing with the smoothies and that they did not handle well in rough water. The company is also quick to point out that elite crews did not use them. Dreher argues that the face of the blade is not as important as back. The goal for Dreher was to maximize lift while minimizing drag.

They focused on many areas including blade angle, thickness, attachment to the shaft, and flexibility. The curvature of the leading edge of the blade offers more advantages in hydrodynamic lift and acceleration by moving the center of press and mass of the blade [11].

In the Apex, the main design change is that the spline was moved to the top of the blade (hence the name). This spline has been smoothed down compared to earlier designs. In addition, the volume contained in the spline has been changed to give the blade buoyancy. The main advantage claimed by Dreher is that they have eliminated obstructions to flow on the back side of the blade giving it quicker releases and faster drives. The fact that these sculls (oars used by scullers) are light (weighing in at a bantum weight of 1.2 kgs) does not hurt their performance either. [12]

After testing the Apex blade, Dreher states that a 0.02 to 0.03 meter per second advantage can be gained by using this blade versus its old designs. In addition, slow motion photography reveals minimal turbulence generated throughout the driving. This leads to the conclusion that blade is more efficient and slips less. Dreher also claims that tests show that "peak" forces occur during the first 1/3 of the stroke. This led to the design of the Apex-R, a variation on the Apex. This blade favors forces during the first part of stroke. Ideally, if the engineers could create a material that could change while in use, the blade would change shapes during the drive from a small ellipse to a large circle at the square off point and then back. Dreher claims the Apex-R does this by melding both shapes into the blade [13].

Both the Apex-R and the Smoothie with the vortex edge have coincided with the international rowing community's desire for more powerful catch angles. To adjust for these powerful catch angles, rowers have reduced their outboard scull length by four to six centimeters. The rower could reduce the spread (or the distance from the oarlock to the centerline) and then adjust the inboard length to maintain the same inboard outboard ratio and adjust for hand clearance in sculls. According to Dreher, true outboard is measured from the oarlock to the center of pressure on the blade, which is contrary to convention [14]. Most rowers measure the outboard length from the oarlock to the blade's tip. Adjusting the spread and outboard length, especially using Dreher's technique, help the rower get a smaller catch angle (from the oar to the shell), thus increasing the load at the catch. Sweep oars get 10° larger catch angle than sculls because they are much longer. This is why a quad (four person scull) is faster than a straight four (four person sweep without a coxswain) and almost as fast as an eight [14].

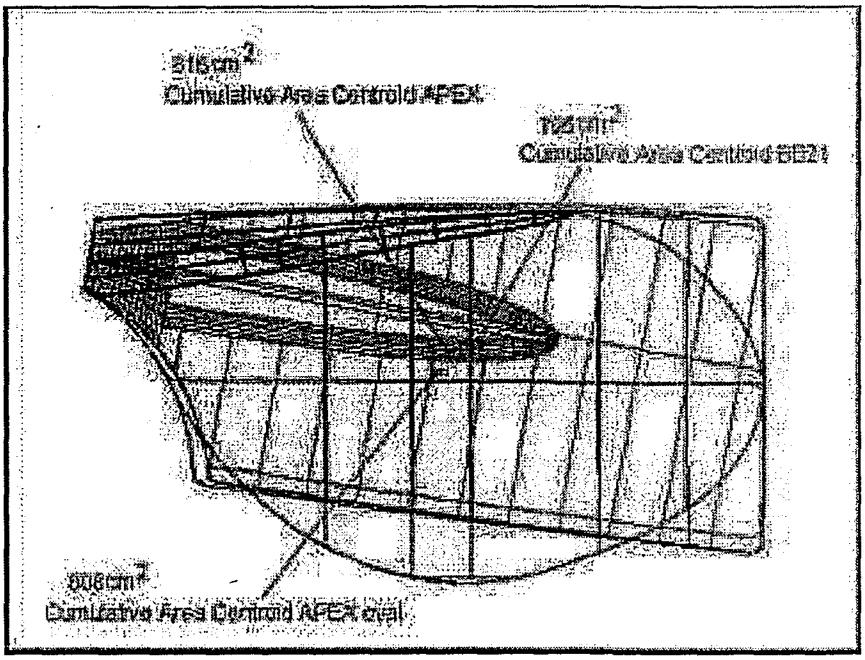


Figure 18: Dreher's Apex Design, vs Dreher's BB21 [12]

The Fat2 Blade is the latest addition to the Concept 2 family. The blade has a larger surface area than any of the other blades Concept 2 currently makes with sweep blades measuring 1212 square centimeters and sculls measuring 857 square centimeters. The Fat2 comes with the vortex edge which leads to the same benefits and loading profiles as the Smoothie2 Vortex. Concept 2 claims that the loading profile is more pronounced (i.e. heavier at the catch and lighter at the finish). Minimizing forces at the end of the drive helps to reduce any energy losses due to the oar moving backwards at this point. In addition, the Fat2 design results in less slippage [7].

Even with the advent of new blade designs, the Dreher-Concept 2 battles have not yielded much in terms of increasing blade effectiveness. Although hatchets are easier to handle than macons, the speed difference is almost negligible. Basically, after 20 years of new innovations and designs, the blade looks similar and the increase in efficiency is hardly noticeable. The two companies have succeeded in making an oar that is easier to control and more comfortable for the rower. By eliminating these variables, crews have become faster. But what about making a truly more efficient oar?

Brearley and de Mestre [15] claim that by adding a positive cant angle $\acute{\alpha}$ to the oar blade, the efficiency would be increased and it would allow for maximum force to be exerted on the oar when the blade is at the square off position. Brearley and de Mestre define the force equation provided by a standard oar that changes slightly due to the shaft bending during the stroke

$$F = B*\cos(\psi + \varphi) \quad (20)$$

Where φ is the bending angle of the oar. At "steady state" or constant velocity

$$2*F = D \quad (21)$$

where D is the drag on the boat and is defined in Equation (14). From Equation (14), the mean velocity can be calculated [15].

If everything is equal, Brearley and de Mestre argue that adding a cant angle is the answer to making oars more efficient. The resulting forward force on the boat after adding a cant angle ($\acute{\alpha}$) is now

$$F = B*\cos(\acute{\alpha} + \psi + \varphi) \quad (22)$$

This assumes that the deviation of the oar angle and the oarlock force remain the same. One must remember that from the catch until the square off point, ψ is negative. Thus, by adding the cant angle, the overall sum of the three angles approaches zero. This causes the cosine term to approach one and a higher force is transferred to the boat from the blade. Brearley and de Mestre used data collected from an instrumented oar and compared it to what could be hypothetically accomplished with an increased cant angle of 5° (see Figure 19) [15].

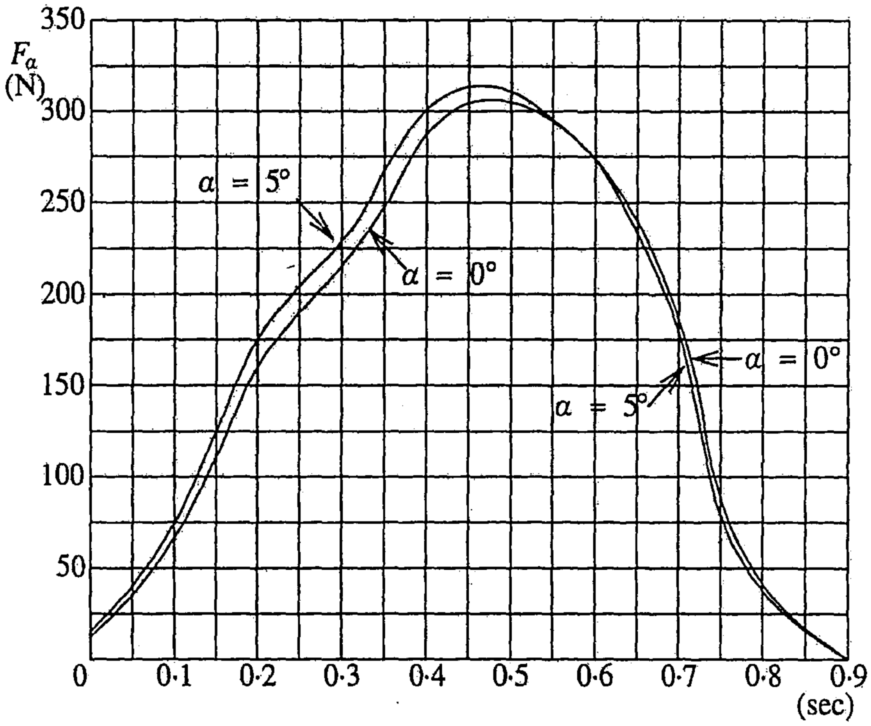


Figure 19: Force Comparison Between Cant Angles of 0° and 5° [15]

The introduction of a cant of angle of 5° will offer better performance during the first 60% of the drive. During the last 40% of the drive, the traditional 0° cant angle will perform better. However, the traditional cant angle cannot overcome the tremendous gains made by the positive cant angle during the first part of the drive. Oars at as little as a 5° cant angle will provide a 1.7% increase in boat speed. The increased boat speed results in a 34 meter lead from bow ball to bow ball at the end of a 2,000 meter race.

This means that if two crews raced and all things were equal other than the oars' cant angles, the crew with the positive cant angles would finish ahead by over six boat lengths [15]. This is the equivalent of a little league team winning by the 10-run mercy rule in the third inning.

To an engineer, the next questions become, "Well, what about a 10° or 20° cant angle? Does more ever become too much?" Brearley states that the bigger cant angle will exponentially add speed to the boat. However, there are problems outside of acceleration with bigger cant angles. With a large cant angle, the oar shaft would intersect the blade on the bow side of the center of pressure. This would cause the oar to become unstable. It is most beneficial for oar stability to have the shaft blade intersection forward of the blade making large cant angles problematic [15].

Another problem with large cant angles is how the oars interact with air flow during the recovery. Larger cant angles would make insertion and extraction of the oar more difficult. Also, the blade would interact with the air flow differently causing it to be unstable during the recovery when the boat is less stable. A biomechanical issue is also encountered here. A larger cant angle could cause back problems for the rower due to a larger load being felt at the catch [15].

Subchapter 3c: Blade Testing

The end result of all these new innovations is to make the boat move faster with the least amount of effort from the rower. An engineer could assume that this is an easy task: simply put an oar in the water and study the flow over the design of the blade. However, this test does not necessarily model all the different positions and water flow types the blade encounters in its path through the water. In addition, it is difficult to model the exact motion of the blade because of the many different paths it takes during the stroke. These models also do not account for the load the rower feels during the stroke and how the blade will sit in the water during the drive.

The test facility is important and it is no coincidence that both Dreher and Concept 2 are located on a calm stretch of river. Both facilities have over a straight 500 meter stretch of "dead" water in their backyards where they perform all their tests. By minimizing current, wind effects, and depth variables, the companies can focus on the differences between blades [7, 11].

Since the 1980's, Concept 2 has logged over 1,250 timed test pieces fine tuning the development of its oars. Its test procedure is as follows: rowing at least three timed pieces with the new design and three with the old. It alternates pieces switching between the old and the new design. Testers attempt to keep all other variables the same (rowers, stroke rate, water properties, boat, Etc) to make sure the only variable changing is the blade design. All pieces are rowed with rowers exerting maximum power [7].

Each test piece is subject to a ten stroke acceleration phase and then a timed 40 stroke phase. During this timed piece, a speed-meter gives the desired data. 500 meter tests are recommended for distance timing. Multiple tests over the 500 meters help eliminate the variables of finishing during different parts of the stroke. For example, a crew finishing a test during the catch will finish slower than a boat finishing during the end of the drive. This is because the boat will be decelerating at the catch point and accelerating during the finish [7].

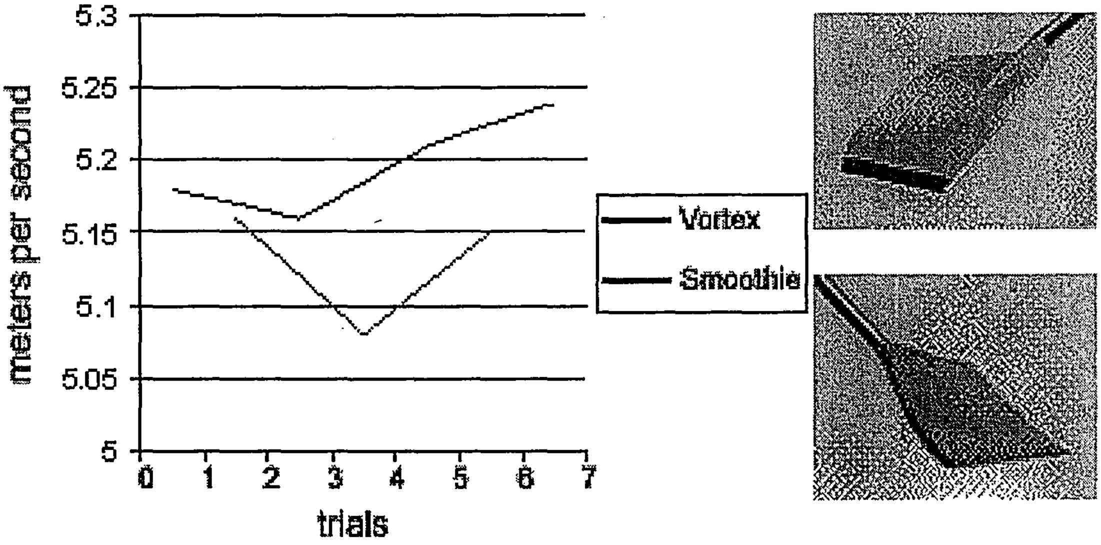


Figure 20: Results from Concept 2s Testing of Two Different Designs [7]

After testing is completed, Concept 2 graphs the data from that day only. Tests are performed over several days (see Figure 20). Concept 2 is quick to point out that this data is relevant for that crew only. The reason that these conclusions are not generalized is that of biomechanics and technique variations. First, the loading and blade performance will depend on the rigging of the shell. The rigging will affect how much catch angle the rower will achieve and also affect the gearing of the oar. Many rowers prefer the feeling of the load at the catch, while others prefer it towards the end of the stroke. Also, coaches differ in their opinions of proper form. Coaches who teach rowers to add power immediately at the catch will prefer different blades than those who are taught to have and extended lay back with forceful finishes. As of yet, no conclusive evidence has been provided as to which style propels the boat the fastest. This combined with the fact that the difference in performance between blade designs is often a few fractions of a second, leads to personal preference being the main driving factor in blade design choice.

Dreher's testing is similar to that of Concept 2's. However, Dreher does make the claim that available new designs are faster. Recently, these improvements in blade designs have resulted in a few tenths of second decrease in 500 meter times. This improvement falls in the error tolerance for the instruments that are used, a deficiency Dreher freely admits to but still makes the claim that the new designs are better [13].

This type of testing does not produce the type of accuracy engineers are used to but it helps keep the cost of the product down. In addition, the complexity of properly modeling the flow of water over a blade to determine the best job is highly complicated and it is only recently that software capable of tackling this giant has become available. In 1998, the Fluid Mechanics Laboratory of Ecole Centrale de Neutes (LMF) created a computer simulation which models the unsteady three dimensional flow over the hull and blade [16].

The genius of this model is that it over comes the main problem that plagued previous models. Previous models were unable to calculate the force and frictional coefficients on flow surfaces and thus relied on user inputs. These older models were simple and two dimensional which ignored the complexity of the situation of adding the third dimension [16].

Another problem that engineers faced, was the complexity and number of equations that needed to be addressed to ensure proper modeling. The LMF developed a computational fluid dynamics solver to deal with the growing complexity of the Reynold's Averaged Navier Stokes' (RANS) equations that model turbulent water flow over any surface. The RANS are a set of simplified time averaged equations that, with known data, can be used to solve the Navier Stokes' Equations. These solutions will provide the appropriate data at each time step for the LMF's model [17].

The LMF's program is a state of the art subscale simulation that will evolve (from run to run) based on the accuracy of its outputs creating a better simulation for the next run. Leroyer [16] tried to evaluate this software in the flow of water over a blade. HE designed an experiment to measure forces and compare them to the ones predicted by the software. The simulated oar was simply a subscale model of an oar blade but with a flat surface. The experiment used a tow tank to simulate the water moving past the blade as described in the previous section. The machine (a dynamometer with 6 components, see Figure 19) models the stroke to near perfection but does not remove or insert the oar into the water.

The dynamometer was programmed with a maneuver that simulated the catch and this minimized the drag differences between the simulation and a rower's true catch. This program also introduced a neutral motion for the oar to simulate the rower's recovery phase. There are various levers to adjust oar depth, length, and drag to simulate a variety of scenarios. Attached to the dynamometer was a test bench which measured the forces and moments acting on the blade during the test and relate these measurements to the position of the blade in the tank.

The experiment consisted of several runs. Before each run, the inertial and aerodynamic characteristics were measured and the center of gravity was adjusted. Each run consisted of a four step process:

1. The "oar" was placed at 0o in the water.
2. The carriage was accelerated to a specific velocity.
3. The blade followed the trajectory described above to 180o.
4. The carriage was stopped.

Force, velocity, and angle measurements were sent from transducers via analog connections. All measurements were filtered to eliminate errors due to noise/static provided by the transducer. Three different numerical simulations were run. The first test was performed with a mesh of 120,000 cells (M12e4) with an adaptive time step. In simulations 2 and 3, a 140,000 grid was used (M14e5) where simulation 2 used a uniform time step of 0.0005 seconds and simulation 3 used an adaptive time step. These meshes are shown in Figure 22. The higher meshes were used to provide more accurate results but it was discovered that these higher meshes might diffuse and lead to a less defined mesh [16].

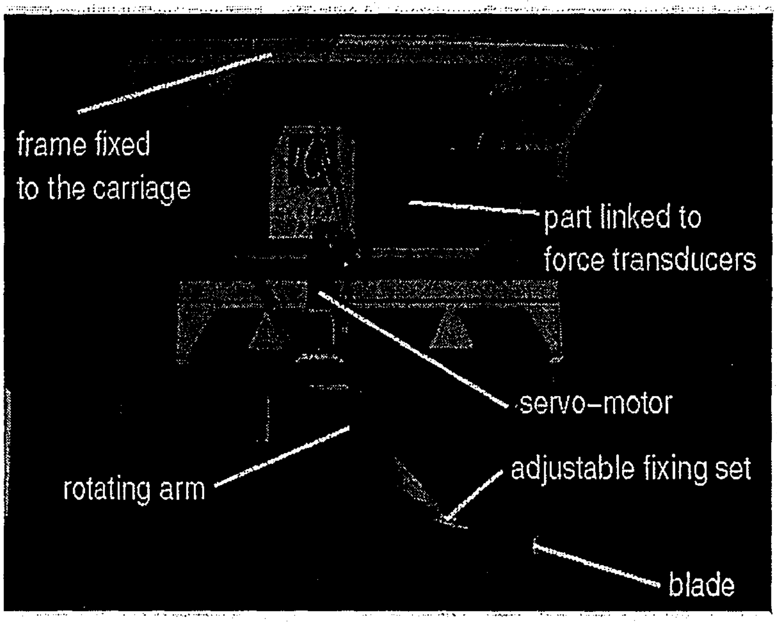


Figure 21: The LMF's Testing Setup [16]

Figure 21 illustrates the test bench which is constantly recording data as to the forces acting on the oar and the position of the blade. Instantaneously, the LMF's software takes multiple theories and modeling approaches and solves them together to find the most accurate models for the given data. The base equation used is the incompressible unsteady Reynold's-Averaged Navier-Stokes equation. The program creates a mesh on the blade's face and begins solving using the finite volume method. The velocity field and pressure variances around the blade are calculated via the momentum conservation equations and continuity equations, respectively. Simultaneously, at mesh points were the flow is turbulent, the solver uses the Spalent-Allmarans model, k-w model closures, and a full stress transport model to estimate the desired parameters.

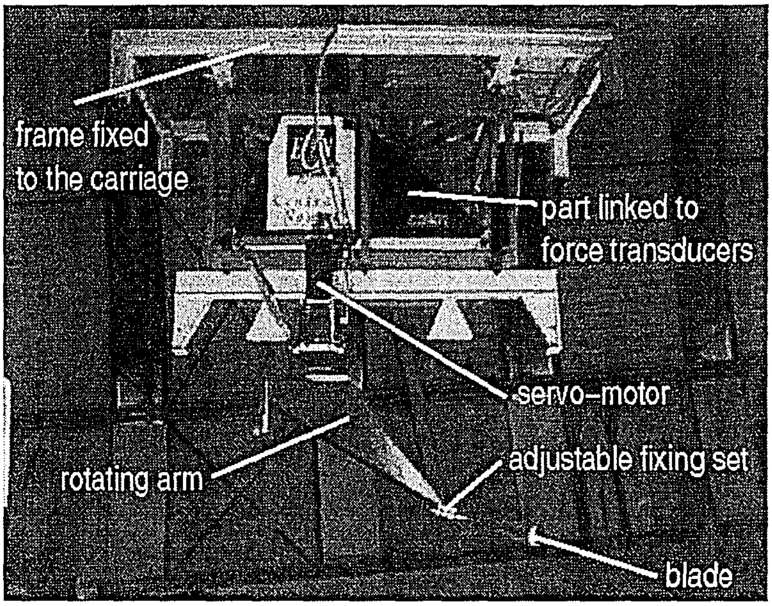


Figure 21: The LMF's Testing Setup [16]

Figure 21 illustrates the test bench which is constantly recording data as to the forces acting on the oar and the position of the blade. Instantaneously, the LMF's software takes multiple theories and modeling approaches and solves them together to find the most accurate models for the given data. The base equation used is the incompressible unsteady Reynold's-Averaged Navier-Stokes equation. The program creates a mesh on the blade's face and begins solving using the finite volume method. The velocity field and pressure variances around the blade are calculated via the momentum conservation equations and continuity equations, respectively. Simultaneously, at mesh points were the flow is turbulent, the solver uses the Spalent-Allmarans model, k-w model closures, and a full stress transport model to estimate the desired parameters.

To ensure accuracy any finite volume/discretization method, the challenge is to keep the grid/time step small enough to ensure the model produces accurate results. This is measured by the Courant Number. Here the Courant Number for multidimensional models is

$$Cou = \Delta t * F/V < 0.3 \quad (23)$$

Where F is velocity flux and V is the upper cell volume [16].

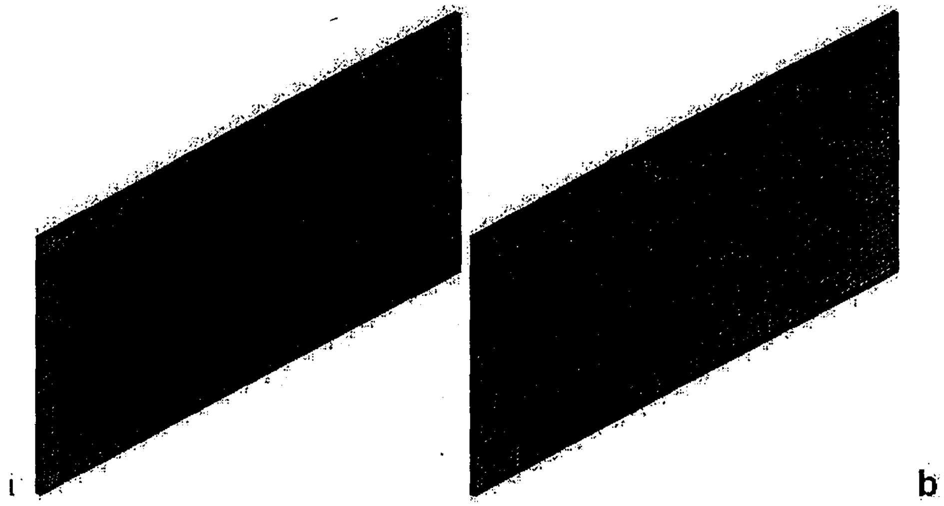


Figure 22: Samples of LMF Meshes (M12e4 Left and M12e5 Right) [16]

Achieving accurate results in this model (even with all its power) was achieved by making some important assumptions. These assumptions included: the blade and oar shaft do not change shape during the stroke; the chord line of the blade is in line with the shaft; the translation occurs in constant velocity; and the blade has a constant characteristic efficiency (we will see later that this is not the case).

To ensure accuracy any finite volume/discretization method, the challenge is to keep the grid/time step small enough to ensure the model produces accurate results. This is measured by the Courant Number. Here the Courant Number for multidimensional models is

$$Cou = \Delta t * F/V < 0.3 \quad (23)$$

Where F is velocity flux and V is the upper cell volume [16].

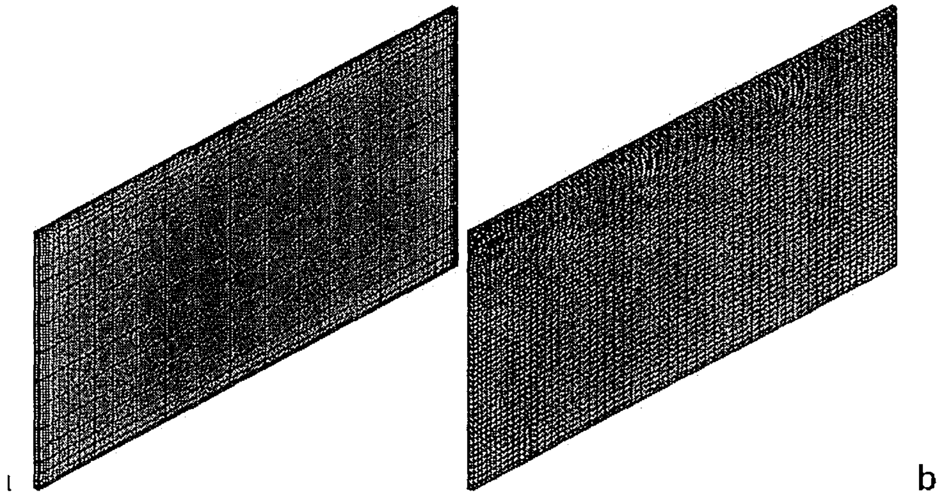
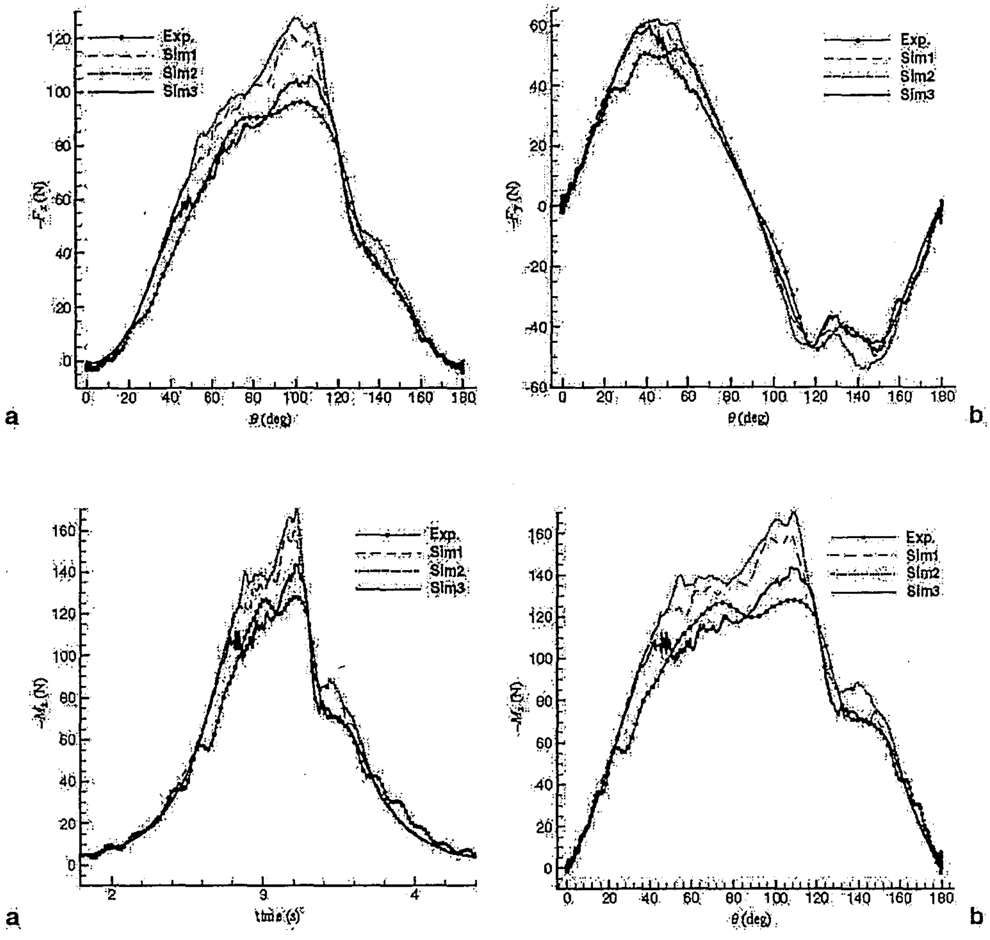


Figure 22: Samples of LMF Meshes (M12e4 Left and M12e5 Right) [16]

Achieving accurate results in this model (even with all its power) was achieved by making some important assumptions. These assumptions included: the blade and oar shaft do not change shape during the stroke; the chord line of the blade is in line with the shaft; the translation occurs in constant velocity; and the blade has a constant characteristic efficiency (we will see later that this is not the case).

The simulations revealed that as the blade moved through the water, a wave like flow develops at the leading edge of the blade. At the same time, the free edge travels to the blade's bottom and generates a "ventilated cavity." This phenomenon generates turbulence and thus decreases the efficiency of the oar. The ventilated cavity begins to diminish as the blade reaches the square off point. This leads to higher efficiencies, which agrees with other studies done in this area (discussed in Chapter 4).

Leroyer [16] confirmed the accuracy of this model by comparing it to experimental data. Figures 23 and 24 show the comparison of the three models with experimental data for hydrodynamic force and torque on the blade. It appears that Simulation 3 (with the 140,000 mesh points and the adaptive time steps) produced the most accurate data compared with the experimental results.



Figures 23 and 24: Hydrodynamic Force Curve (Top) and Hydrodynamic Torque (Bottom) [16]

The tests at the LMF revealed many problems with utilizing these results in the real world. It was noted that different styles of rowing produce unreliable velocity data. Furthermore, the number of parameters associated with measuring fluid flow (even with the brawn of the LMF's model) created problems in accuracy. However, the simulations did provide accurate data when compared the experimental results. As computers become stronger and processing time shortens, simulations will become a more viable solution for studying hydrodynamic flow over the face of an oar. As new designs for blades emerge, the accuracy of these simulations will provide more detailed information as to whether or not the new design is better. The LMF's simulations will provide more accurate information when compared to the tests currently available to Concept 2 and Dreher.

Chapter 4: Mechanical Efficiency

Effort has to be applied to any machine but the definition of the efficiency of a machine is the ratio of work it returns over the effort applied. As discussed in Chapter 2, an oar is a machine (a lever), and the effort is applied by the rower to the handle. This leads to the next question: How efficient is the oar at transferring energy into the propulsion of the boat?

The boat's efficiency has been commonly defined as work done by boat drag divided by the work done by the rowers, and drag. This equation mathematically becomes

$$\eta = boat\_dissipation / total\_dissipation = D_b / (W_{\text{int}} + D_b + D_{oar}) \tag{24}$$

Where D_b is the shell's drag, D_{oar} is the blades drag and W_{int} is the work done by the rower. The assumptions made here are that pitch and yaw of the boat are minimal, the oars are similar in size and mass, and the blade force is perpendicular to the blade (which as stated in Chapter 2 is debatable). Work done by drag comes from both the oars and boat as defined by

$$D_b = \left| \int_0^t - v_b^3 * C_b \, dt \right| \tag{25}$$

$$D_{oar} = \left| \int_{t1}^{t2} F_{oar} * (l * \theta' + v_b \cos(\theta)) dt \right| \tag{26}$$

Where C_b is a experimental drag coefficient, t is the time for a stroke, t_1 is the time for the catch, t_2 is the time for the release, θ is defined in Figure 3, and θ' is defined in Equation (3) [18].

It is assumed that D_{oar} is only non-zero during the drive period. This assumption is only valid with an experienced crew who can maintain the set (balance) of the boat since air resistance is negligible. If the crew cannot do this, then the blade will drag on the surface of or below the water during the recovery contributing significantly to the drag.

Macrossan takes this definition deeper and a few steps further. He stated that efficiency is dependent on rotational power input and output.

$$\dot{E}_{in} = B * \theta' * l \qquad (27)$$

$$\dot{E}_{dis} = -(B * v_n + B_t * v_t) \qquad (28)$$

Where l is defined in Equation (2), B is defined in Figure 3, B_t is the tangential blade force, v_n is as defined in Equation (4), and v_t is defined in Equation (5). Thus the efficiency equation becomes

$$\eta = (E_{in} - E_{dis}) / E_{dis} = B_t * v / (B_n * \theta' * l) \qquad (29)$$

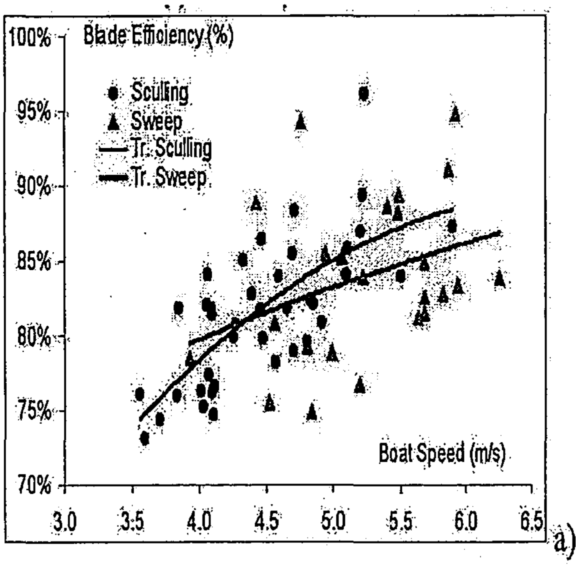
Using this equation and experimental results, Macrossan came up with an efficiency of 72 to 90% from the oar catches to when the oar is normal to the boat. He also found that higher boat speeds increase efficiency [1].

Other less common definitions for efficiency, which vary with the point of view of the observer, are the ratio of useful work done to total work done and the ratio of crew work to the sum of oar drag and crew work dissipation [18].

The greatest contributor to the overall efficiency of the boat is stroke rate. During a study that incorporated 71 rowers from 21 crews at the University of Massachusetts, Kleshnev [18] used a Nielsen-Kellerman Speed Coach to measure velocity, a piezoresistive accelerometer to measure acceleration, and an inductive proximity sensor to measure the force applied to the oar. With these instruments he calculated the boat efficiency by the propulsive power (power applied) divided by the velocity fluctuation of the shell (Power "wasted"). These calculations revealed almost a 0.72 loss in efficiency (from 1.4% to 2.4%) by increasing the stroke rate from 20 strokes per minute to 40. However, the mean velocity did increase significantly, which is why coaches have their crews race at higher rates.

Similarly, Kleshnev [19] pointed out a second factor that had a significant influence on the efficiency of his study. Rowers and coaches are familiar with this concept, "Ratio." There are few practices and races where this word is not heard. Ratio is simply the proportion of time of the oar is in the water (drive time) to the time oar is out of the water (recovery time). Ratio is dependent on the stroke rate and on the rower's ability to move the boat past the oar or power. Kleshnev's study revealed that ratio is important at all stroke rates. The faster the rate, the faster the drive must be to maintain the proper ratio [19]. With a faster drive, more power must be exerted on the oar. Thus, stroke rate is linked to the overall velocity of the boat in the form of a linear regression equation [20].

Competitive rowers especially care about the efficiency of the machine as a whole. They want to go faster. Thus the most important device is the oar which transfers their energy to the boat's velocity. As seen in Figure 25a, the more efficient the oar is the faster the boat will travel. The rower must compensate for extraneous energy lost due to set and blade slippage. Slippage is the major cause for the loss of energy from the oar (as discussed previously in chapter 3). Basically, the less an oar slips, the less energy is lost which equals better efficiency. An easy and quick response is to have the rower to add more power in the stroke to increase efficiency and add it when the oar is perpendicular to the boat. However, the delta in force would change the efficiency curve. More force would result in more oar slippage and a decrease in efficiency [1]. Thus by eliminating slip one would maximize efficiency. Slippage for any oar is reduced at low velocities but oar force is minimal.



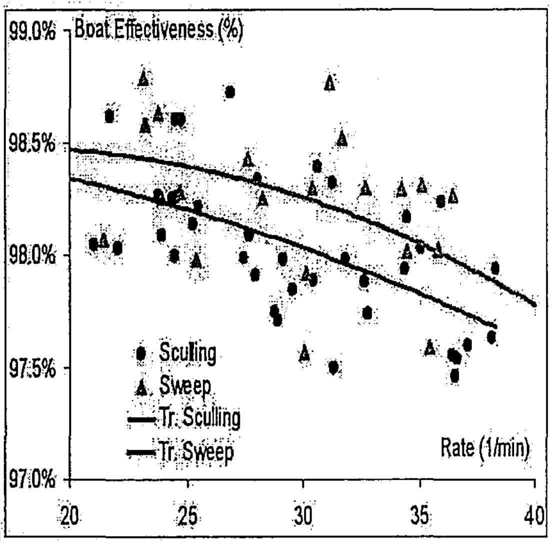


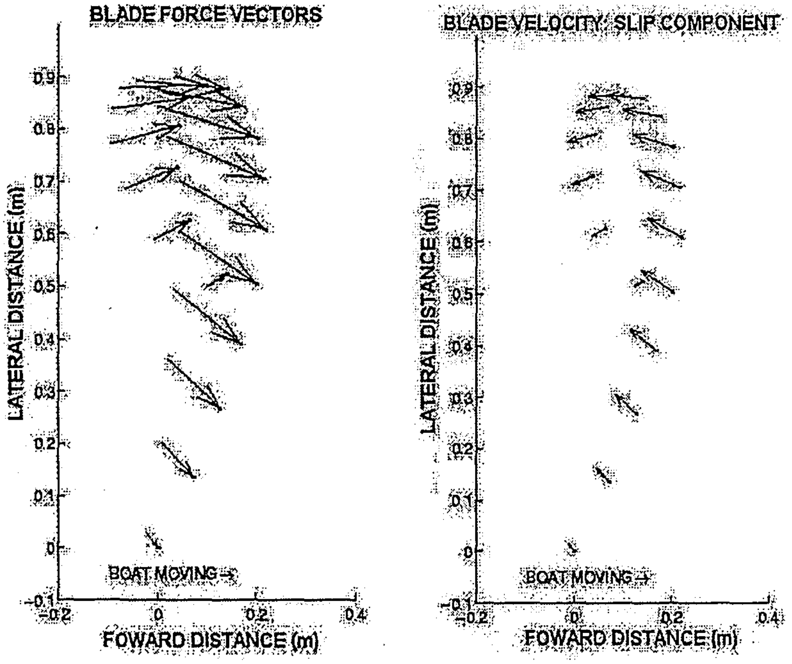
Figure 25a: Velocity vs. Blade Efficiency

Figure 25b: Stroke Rate vs. Boat Efficiency [20]

Kleshnev [20] also explored the factors influencing the efficiency of the blade. His studies revealed that the efficiency of the blade was dependent on the number of rowers in the boat. The more rowers in the boat the more efficient the blades became. The blade efficiency for an eight man crew was up to 7% more efficient than that of a single sculler. This probably has to do with the size of the oars and the number of the oars. Bigger blades reduce slippage but increase the load the rower feels. Scullers use smaller blades than sweep rowers because they are handling two oars at a time, which are also smaller in length. However, the blade size does not differ with the number of rowers. The more oars applying force to the oar lock in proportion to the weight of the boat will help move the boat before the oar succumbs to slippage. Thus more power applied to the oar blade(s), the higher the efficiency. The study also revealed a relationship between form and blade efficiency, although this is harder to quantify.

Simplified, depending on where and how pressure was applied to the handle by the rower affected the efficiency of the blade. Overall, Kleshnev [20] claims a larger gain in efficiency will be obtained by eliminating slippage (5.0%) than by trying to keep the boat at a constant velocity (0.8%) [19]. He backed this theory with a study done on boats which medaled at the Sydney Olympics. For sweep boats (those with one oar per rower), the crew that maintained the higher stroke rate placed higher [20].

Blade efficiency is linked to the direction of the water force on the face of the blade. However, blade force may not always act normal to the blade, thus, making efficiency difficult to determine. The pressure differential along the face of the blade, if equivalent on both sides, transfers the net force to be perpendicular to the face of the blade. The force vectors direction and magnitude are shown in Figure 26 in comparison with the slip component's direction and magnitude.



(a) Blade force vectors (b) Slip velocity vectors

Figure 26: Force and Slip Vectors Over the Blade's Path [21]

Macrossan and Macrossan [21] state that efficiency can be defined in a different approach. This approach can be explained as the ratio of the amount of energy dissipation from blade slippage over the product of the effort applied at the handle and the angular velocity. This leads to the oar efficiency being

$$\eta = 1 - \dot{E}_{slippage} /(T * \theta') \tag{30}$$

Where T is the torque applied at the handle. The team states that this equation is more accurate than those discussed above because force direction has little effect on the efficiency of the blade. Thus, their definition does not rely on the direction of the force on the blade but rather the amount of slippage that occurs.

Here by making a simple solution into Equation (18), the physics becomes clearer. Let v_s be the velocity at which the oar slips. By the definition of slippage provided above, v_s must equal v_n as defined in Equation (4). This leads to the rate of energy dissipation by the oar as:

$$\dot{E}_{blade} = B_n * v_s \qquad (31)$$

The rate of useful energy or that which is transferred to propelling the boat forward would become

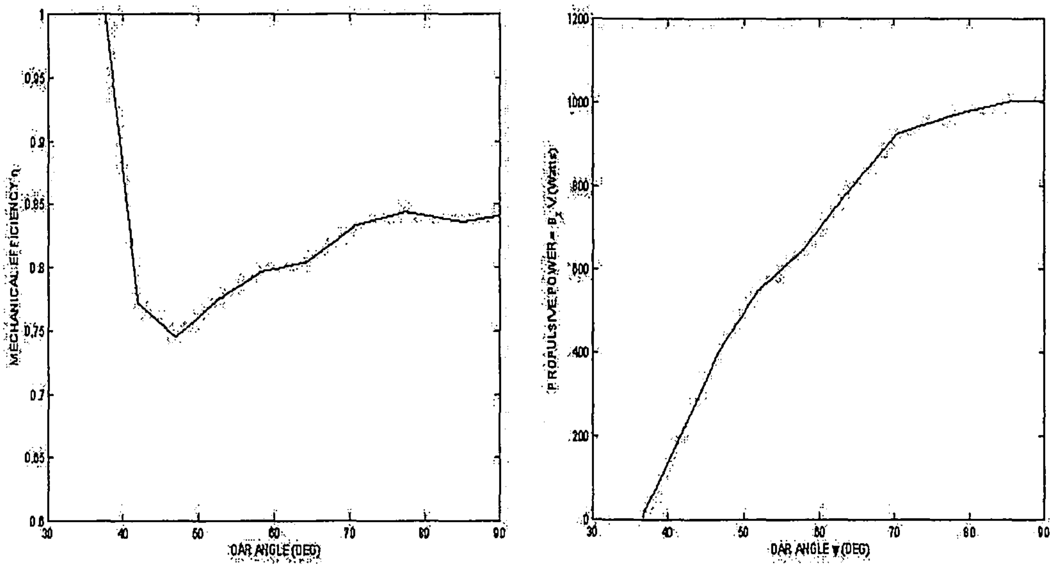
$$\dot{E}_{prop} = \dot{E}_{rower} - \dot{E}_{blade} \qquad (32)$$

Thus by lowering the slippage velocity, the blade would become more efficient by transferring more energy to the boat.

This leads to the conclusion that a blade that does not slip would be 100% efficient. Macrossan and Macrossan [21] contend that a 100% efficient rowing is probably impossible if the blade force does in fact act normal to the face of the blade. This is because when $v_s = 0$, the force applied to the blade must be minimal. This small force probably would not be enough to move a boat. When enough force is added to the blade to move the boat, it will slip and, therefore, never be 100% efficient.

Well if the blade can never be a perfect machine, then when is at its best? Testing revealed that at the instant the blade is dropped in the water it is near 100% efficient (see Figure 25), but as soon as the rower applies any effort to the handle, the blade's efficiency drops dramatically (almost 40%).

The blade becomes more efficient through out the stroke, reaching its peak near the square off point (about 84% efficient) [21]. There are a few reasons for this reaction. At the catch, the rower has yet to apply pressure and thus the blade will not slip. As soon as the rower adds pressure, the blade begins to slip. Here the blade's velocity is at an angle to the blade force and thus does not counter it fully, allowing the blade to slip more. As the stroke progresses, the boats speed increases which decreases the amount the blade slips. When the blade reaches the square off position, its velocity is acting directly in line with the blade force. This minimizes the amount the blade will slip [20]. Figure 27a illustrates the average efficiency of all blades in a boat from catch to the square off position for an elite boat and 27b shows the average power applied at the handles for the same boat.



(a) Efficiency η (b) Propulsive power $\dot{E}_{prop}$

Figure 27a: Efficiency vs. Oar Angle

27b: Power vs. Oar Angle [21]

The team tested their theories with the help of data collected by Dr. Kleshnev. Dr. Kleshnev obtained her data via the use of an instrumented boat and oars which collected data over 50 equal time intervals (or about every 0.055 second) from the catch to the square off position while the crew was rowing at a rate of 21.1 strokes per minute. This was repeated for many cycles and the results averaged.

During this study, Macrossan and Macrossan [21] revealed a conundrum in rowing. In general, the more effort applied at the handle or the more powerful a rower is, the less efficient he/she is. This is seen in the comparison of rower #4 and rower #2 from Table 2. The rower is applying more power to the oar less efficiently due to the increased slippage he experiences. This was as the team expected. However, rower #7 was both more powerful and more efficient than rower #6. This was an unexpected result. The team determined that while rower #7 was more powerful, he also applied the power more efficiently through out the stroke.

Rower #	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**Average**
η	0.821	0.825	0.816	0.817	0.793	0.859	0.907	0.846	0.84
Ep (W)	761	910	787	923	939	872	736	812	843
Bmax (N)	235	314	274	290	333	251	237	249	273

Table 2: Results of Efficiency Data Collected for a Men's 8 Crew [21]

This information was in agreement to what was presented from Kleshnev earlier. He stated that the larger force applied to the blade the less efficient the boat would become. Macrossan and Macrossan's results agree with this. As their study revealed, it

The team tested their theories with the help of data collected by Dr. Kleshnev. Dr. Kleshnev obtained her data via the use of an instrumented boat and oars which collected data over 50 equal time intervals (or about every 0.055 second) from the catch to the square off position while the crew was rowing at a rate of 21.1 strokes per minute. This was repeated for many cycles and the results averaged.

During this study, Macrossan and Macrossan [21] revealed a conundrum in rowing. In general, the more effort applied at the handle or the more powerful a rower is, the less efficient he/she is. This is seen in the comparison of rower #4 and rower #2 from Table 2. The rower is applying more power to the oar less efficiently due to the increased slippage he experiences. This was as the team expected. However, rower #7 was both more powerful and more efficient than rower #6. This was an unexpected result. The team determined that while rower #7 was more powerful, he also applied the power more efficiently through out the stroke.

Rower #	8	7	6	5	4	3	2	1	Average
η	0.821	0.825	0.816	0.817	0.793	0.859	0.907	0.846	0.84
Ep (W)	761	910	787	923	939	872	736	812	843
Bmax (N)	235	314	274	290	333	251	237	249	273

Table 2: Results of Efficiency Data Collected for a Men's 8 Crew [21]

This information was in agreement to what was presented from Kleshnev earlier. He stated that the larger force applied to the blade the less efficient the boat would become. Macrossan and Macrossan's results agree with this. As their study revealed, it is not the force applied to the oar but the boat's velocity that increases the efficiency of the oar by decreasing the speed of oar slip (v_s). This agrees with the results that showed an eight man hell to be more efficient than a single sculler. The eight is much faster than the single and thus blade slippage is reduced greatly. As both the Macrossan team and Kleshnev agree, blade slippage has the greatest effect on the efficiency of the oar and system as a whole [21].

Efficiency losses do no only occur at the blade. Kleshnev states that the velocity oscillations are a contributor to the loss in efficiency of the shell. Both her results and the Macrossan team's show that although a factor, speed oscillations/boat drag only minimally affect efficiency. Speed oscillations contribute to a loss in efficiency around 0.8% while blade slippage contributes more significantly at about 8% [22].

At higher rates, the velocity oscillations are smaller because there is less time during the recovery for the boat to slow down. This would minimize the efficiency lost. The loss in efficiency at higher rates probably comes from the rowers increasing the speed of their drive (i.e. applying more power to the oar handle) to reach the higher rates [22, 23]. More power applied to the handle will result in more slippage of the oar. However, the higher velocity of the boat counters this slippage. This is why there is not a dramatic drop in efficiency while doubling the stroke rate seen in Figure 25b (only about 2.0%).

A more analytical approach was described by Cabrera and Ruina [18]. They decided to base there efficiency equation on oar slip velocity and blade drag. The force of the oar can be defined as

$$F_{oar} = C_2 * (v_b * \cos\theta + l * \theta')^2 \qquad (33)$$

Where C_2 is dependent on the area of the blade and its depth in the water. With this equation, D_{oar} becomes

$$D_{oar} = \int_{t1}^{t2} C_2 (v_b * \cos\theta + l * \theta')^3 \qquad (34)$$

Which can reduce the efficiency equations even further when oar angles are small

$$\eta = (1 + C_2 / C_1 * (v_s / v_b)^3)^{-1} \qquad (35)$$

In Equation (35), increasing the blade area would increase the drag coefficient (C_1) and thus make the oar more efficient. However, this has limitations due to the weight of the oar, ease of extraction and insertion, the increased load placed on the rower, and the energy cost to move the oar [18].

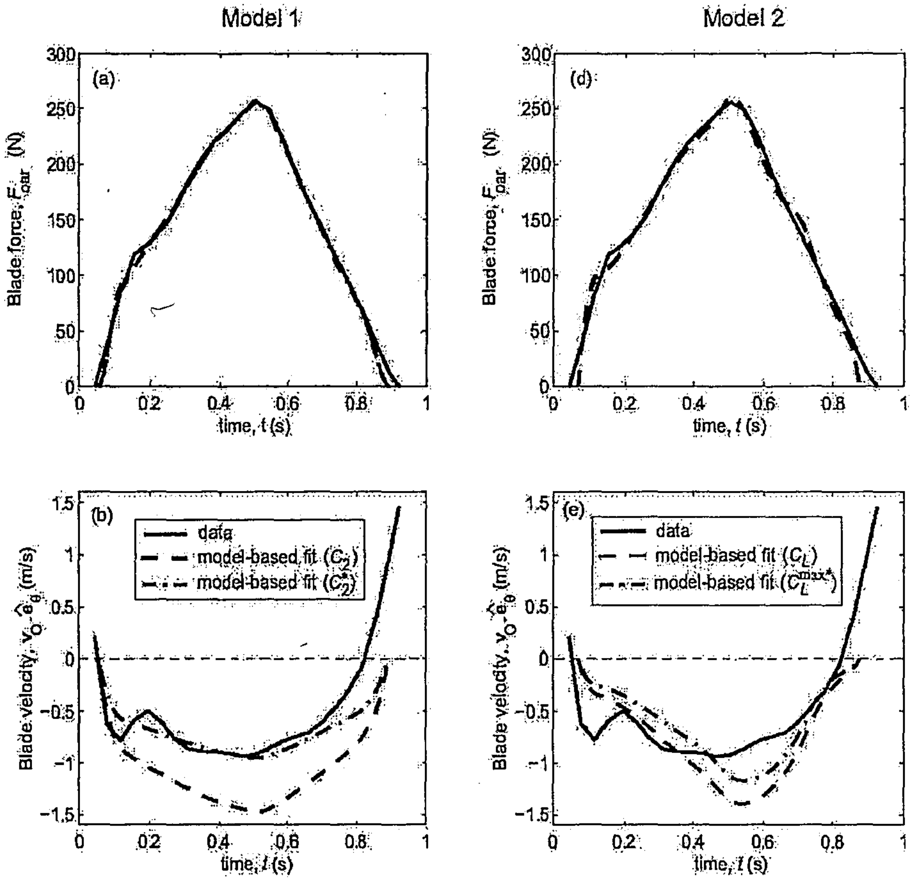


Figure 28: Comparison of Cabrera and Ruina's Model for Blade Force and Velocity with Testing Data [18]

Finally, there's energetic efficiency. Energetic efficiency as defined by Cabrera and Ruing is the ratio of the energetic benefit to the energetic cost. The energetic cost is the work done by the rower to move the boat, oar, himself, etc. The benefit is the proportion of energy that actually transfers to boat movement. Thus

$$\eta = D_b / W_{rower} \qquad (36)$$

An increase in efficiency will be achieved if the blade has a limited force component in the blade drag direction (the force component parallel and opposite to the blade). This theory was first proposed by Wellicome in 1967 [18]. He surmised that due to the vortices at the end of the blade, hydrostatic forces do not act perpendicular to the blade early in the stroke. This assumption leads to better efficiency when the blade is close to the catch and finish of the stroke than would be expected [18].

There are those individuals who believe that hydrostatic forces do in fact act perpendicularly to the blade. Contrary to Wellicome, oar manufacturers have developed various designs for the leading edge of their blades to move the turbulence away from the oar face eliminating slip such as the vortex edge described in Chapter 3b. [15]

Chapter 5: Rowing On Uncertain Waters

As the previous four chapters have shown, rowing is a combination of an art and a science. That combination creates many uncertainties which lead to speculation of what may be best for making the fastest boat. Engineers often fall into the trap of over simplifying rowing equations, which lead to erroneous conclusions. Coaches are not immune to this oversimplification either. In an attempt to correct form and technique, coaches will often preach an ideal that actually counteracts what they are trying to accomplish in the long run, making the boat go faster. This is probably why rowing technique has shifted back and forth among differing techniques for the past 100 years. Below, some of the most prevalent and or prevailing ideas are challenged and hopefully clarified based on the research found in the previous four chapters.

5a. Asynchronous Rowing (Rowing Out of Phase)

Sitting on the shore line, spectators marvel at how a well trained crew oscillates back and forth in perfect synchrony, although few understand why. It is considered such an art and marvel that crews have become the icon for teamwork in commercials, movies, and inspirational posters. But does it have any value other than ascetics? Crews have moved in synchrony from the days of slave ships where the coxswain pounded a drum to synchronize the stroke rate of the rowers. However, it was soon ascertained that the boat's velocity slows considerably during the recovery of each stroke. The shorter this recovery, the less the boat slows. This was shown earlier where the highest boat velocities were obtained at higher stroke rates, i.e. where the recovery is the shortest. If shorter is better, what about no speed oscillations? This can be accomplished in rowing asynchronously in one of two manners.

The first method discussed is the older of the two. This involves an eight man shell rowing out of sync. The stern four rowers are perfectly out of phase with the bow four rowers. Thus, when the stern four were amidst their power stroke, the bow four would be in the recovery phase of the stroke (see Figure 29, below). Since four rowers would be in the power phase at any given time, the speed oscillations would be removed from the boat, velocity would remain constant, and in theory efficiency would increase.

However, crew shells are not designed for this type of rowing. In traditional designs, the rowers are too close together to allow for this type of asynchronous rowing without rowers hitting each other or blades interfering at the catch and finish. A longer hull would have to be developed to accommodate this style but this would add additional drag. Could this extra efficiency make up for the added drag?

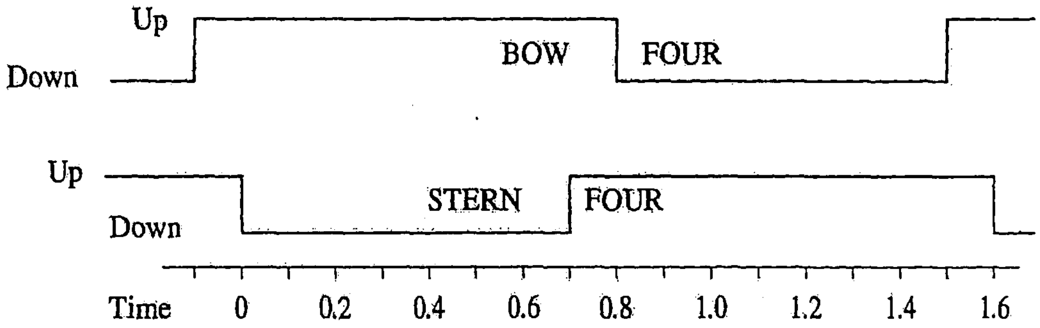


Figure 29: 2 Phase Rowing Detail [23]

Up is the Drive Phase; Down, the Recovery

Brearley, de Mestre, and Watson [23] noticed the possibilities of asynchronous rowing while developing an equation that modeled the velocity of a crew shell and attempted to answer this question. The following differential equations were used to model the stroke of traditional (synchronous) rowing styles:

Drive phase: $dv/dt=K_1\sin(n*t)+K_2\cos(n*t)+A+Bv+Cv^2$ (37)

Recovery: $dv/dt=K_3\cos(n_2*t)+A+Bv+Cv^2$ (38)

Here the velocity is measured in meters per second and time is in seconds. When the team used this to model a crew rowing at approximately 38 strokes per minute (a good pace for racing), the drive is valid for $0 \leq t \leq 0.7$ and the recovery equation is valid for $0 \leq t \leq 0.9$. Here the constants are defined as: K1 = 1.8577; K2 = -5.9695; K3 = 3.6112; A = -0.030182; B = 0.013584; C = -0.015799, $n_1 = \pi/0.7$ rads/sec, and $n_2 = \pi/0.9$ rads/sec. These equations were obtained by solving the above equations using the Runge-Kutta method, with the initial condition that $v = 0$ at time t = 0 and then fitting the solutions to the experimental data collected. This was repeated for each stroke over the duration of a race peace (about 220 strokes).

Through equations (37) and (38), Brearley et al noticed that the deceleration of the boat during the recovery lowered the efficiency of the system. The team of scientists/engineers decided to apply their model to the asynchronous rowing described above. In analytically testing the drive equation, they made the following assumptions:

1. The boat rowed is an eight man shell with coxswain
2. Two meters of modifications to the shell were made to accommodate the asynchronous style
3. Rowers were trained to row in this manner

With these assumptions, equation (37) becomes for $0 \leq t \leq 0.7$

$$dv/dt = 1/2 * K_1 \sin(n_1 * t) + 1/2 * K_2 \cos(n_1 * t) + 1/2 K_3 \cos n_2 (t + 0.1) + A + Bv + Cv^2 \quad (39)$$

And the recovery for $0 \leq t \leq 0.1$ (due to the overlap at time steps 0.7 and 0.8 see Figure 26)

$$dv/dt = 1/2 * K_4 \sin(n_2 * (t + 0.4)) + A + Bv + Cv^2 \quad (40)$$

Where $K_4 = K_3 \cos(0.4 * n_2)$.

Through computer analysis, it was found that traditional synchronous rowing yielded an average distance of 9.49 meters per stroke, while asynchronous rowing yielded a larger 9.59 meters per stroke. From rest, the synchronous rowers have the advantage in overcoming the initial inertia since all eight are adding power at once. But within the next ten strokes, the apparently more efficient 2-phase rowing gains enough speed to pass the traditional rowers [23]. This is seen in Figure 30.

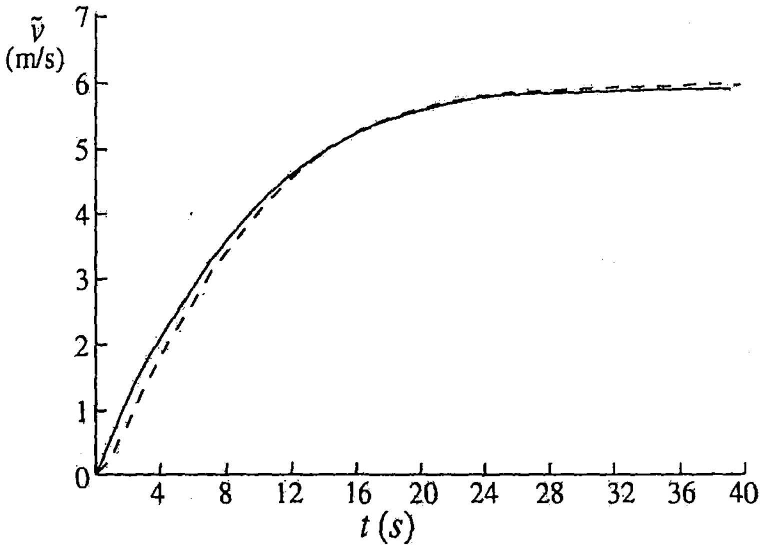


Figure 30: Comparison of the Velocities of Single Phase (solid line) and 2- Phase Rowing (dotted line) [23]

Given that it takes a comparable length of time to complete both types of strokes, the asynchronous boat would finish a 2,000 meter race by just over a full hull length advantage. This was also true when the equations included the extra drag that would be needed to ensure the oars had proper clearance. Brearley et al suggest that rowers start off rowing traditionally to get the boat past the initial inertia and then transition to 2-phase rowing for optimal speed [23].

A newer more complex idea has emerged and made its way to the internet. In this method of rowing, instead of having the crew row as fours, each rower rows as an individual. It is called the "centipede" method of rowing. Each drive phase would begin with the stroke or eight seat catching then each rower behind him starting sequentially at set intervals [24]. The time of the drive phase must be consistent for each rower in order for this to be accomplished. This is also the case for traditional styles and should not be problematic. The drive time would be divided by seven to ensure that at any given time step there are seven oars in the power phase with one oar finishing the recovery. Realizing that this timing would be difficult to maintain, the author of the source (although probably not the style), Mr. Goodfellow, suggests that each rower wear a headset in which his or her seat number would be heard when it was time to start the next stroke [24]. This could also be done over the current speaker system in the shell from which the coxswain gives commands.

In addition to the boat having continuous momentum, this style offers a few other benefits versus the style suggested by Brearley's team. One such advantage is that in this method there would be seven rowers in some part of the drive phase vice the four described above. The boat might be faster due to the added rowers, although it is difficult to determine because the rowers would be in different elements of the drive and, as discussed before, these phases do not contribute equally to the acceleration of the boat. The second advantage is that conceivably no modifications would have to be done to the boat because each rower would be at different part of stroke allowing them to move freely of each other. Thus, no extra drag from lengthening the shell would be incurred.

Mr. Goodfellow and Brearley's team admit that this is not a new concept and it has been around for years. In fact, there is a news clip/reel from 1930 showing an eight man shell rowing in a combination of the above two styles [25]. Here, each member if the eight rows in pairs synchronously together but out of phase with the other pairs in the centipede motion described above. The news clip even explains the physics of removing the speed excursions from the shell. There are also unconfirmed anecdotes of a boat that placed the coxswain in the middle of the boat to allow the rowers in the stern and bow to row in a two phase style. An international boat won the World Championships in the

1970's with a boat that was designed to row asynchronously but during the competition this boat was rowed in the traditional style [26]. So why does it not work or is there a conspiracy by rowing traditionalists to keep the sport "pretty"?

In order to answer this question, the physics of how power is applied to the blade must be defined more precisely. Kleshnev [27] states that in a typical rowing stroke performed by a trained rower, 52.8% of the power applied to the oar blade is applied at the handle of the oar. This leaves the other 47.2% of the power to be applied through at the foot stretchers. At first, this sounds counter productive because the feet apply pressure in an opposite direction to that of the boats velocity. As written in Chapter 2, it was determined that at the catch the pressure applied to the foot stretchers actually slows the boat down. The difference is that the instant the blade hits the water and begins to move the boat past it. When the rower applies a force to the oar, an equal and opposite force is applied on the rower. The pressure applied by the rower at the foot stretchers keeps the rower in balance. Hence, the pressure applied at the foot stretchers is passed through the shell and rigging to the oar. In addition the rower must move the oar relative to himself. This is accomplished using the remaining 52.8% of the rower's power. Since the foot stretchers are affixed to the boat as is the oarlock through the rigging, the force that is applied to the foot stretchers is also applied at the oarlock. This force presses on the oar shaft that is contacting the oarlock and acts against the water force at the blade [29]. This propels the boat forward. (See Figure 31) It is the power applied at the foot stretcher that will be the Achilles' heel of asynchronous rowing.

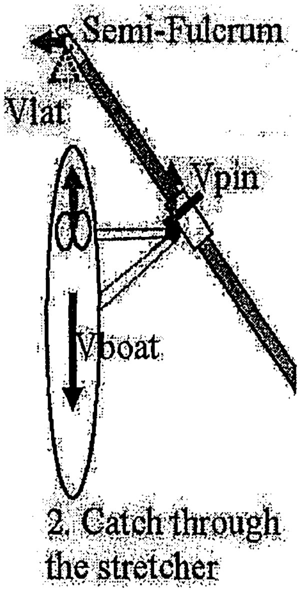


Figure 31: Power Distributed Through the Foot Stretcher [30]

Dr. Atkinson discovered the source of this unexpected discrepancy through his computer modeling software, ROWING [6]. This computer model allows the user to edit almost all of the variables that affect rowing. Dr. Atkinson decided to test this old riddle using his software. In editing the variables, both boats were given equal values in power, boat length, etc. The only difference entered was for the asynchronous boat. The boat was given infinite inertial mass for the shell. By giving the shell infinite inertial mass without increasing the weight of the shell, this would simulate perfect asynchronous rowing by not allowing the rower to accelerate the boat (i.e. eliminating speed oscillations) without increasing drag. To his surprise (and many others probably), the program revealed information that gives the upper hand to traditional rowing and might, forever, end the idea of rowing like a bug walks [31].

Atkinson's software revealed that the asynchronous style of rowing was more than 2% slower when compared to traditional rowing. The reason: the foot stretchers. The physics that makes asynchronous rowing appealing is also its demise. When the boat reaches a maximum constant velocity (the speed oscillations in the boat cease), the foot stretchers stop moving with respect to the rowers. The foot stretchers essentially act as those used for a rowing machine, fixed in place to the machine [32].

Work equals force times distance traveled. Here

$$W_{footstretchers} = F * s_{footstretcher} \quad (41)$$

Where $s_{footstretcher}$ is the distance the foot stretcher moves in relation to the rower. The foot stretchers in asynchronous rowing act stationary with regards to the rower and thus the distance they move is zero. By deduction, the work done at the stretchers is now zero [32]. The rower loses the 47.8% of the power generated through the foot stretchers. The asynchronous crew is now applying just over half as much pressure to the oar blade as a traditional crew. This loss of power more than negates any gains made by the loss of speed excursions.

There are also several other uncertainties that will mar the attractiveness of asynchronous rowing. The first applies mainly to the centipede style of rowing (although would probably effect the 2-phase cycle proposed). If rowers are catching at equal sequential intervals, blades will enter the water in the "puddles" created by rowers who have finished the drive in front of them. Mr. Goodfellow argues that this "may" be a benefit to rowers [24]. However, this is not the case. As described in Chapter 3, turbulence is the blade's nemesis. These puddles are vortices of turbulent water traveling past the boat. If a rower were to insert his/her blade into one of these puddles, the blade would experience more slippage. Slippage reduces the efficiency of the blade and thus the ability to move the boat. As discussed in Chapter 4, slippage is the main reason for loss of efficiency in rowing.

The second problem that asynchronous rowing faces, which only applies to the centipede style, is the shifting of the boats velocity vector direction back and forth. At any given time interval, only seven rowers would be rowing. This would create an uneven distribution of power on each side. This uneven power distribution would create a moment around the axis of the boat. The moment would change the direction of the boat's velocity during that time interval, say to port. As the next rower added in and one dropped out, the boat would shift back to starboard. This would create extra inertia on the shell as well as slightly increasing the distance the boat travelled.

5b. Back Splash

Now that the boat is rowed synchronously, the crew will be performing the same actions at the same time. The catch is arguably the most critical part of the drive since it is what sets up the acceleration phase of the boat. From the above paragraph, it can be deduced that all catches will be simultaneous. But how does one perform the perfect catch?

Back splash is any splatter or splashing of water towards the bow of the boat or to the back of the rower as the blade enters the water. If the oar hits the water as it rotates towards the bow, it will push water in the direction of the boat's velocity. The reader may wonder at first why back splash is a controversial issue. The first thought that would come to mind is that any contact the blade makes with the water during the recovery is detrimental to the overall speed of the boat. Coaches often have a bit of a different idea.

A common problem amongst novice rowers is "driving into the catch" or "missing water." This is where the rower starts his/her drive before inserting the oar blade into the water. The early drive force will cause pressure on the foot stretchers before it can act through the oar on the water. Without the blade in the water, the energy transferred through the foot stretchers will act against the boats velocity. Coaches often solve this by telling the rower to think of rowing backwards into the water or to insert the oar blade as it traveling towards the bow. Cunningham agrees that this misconception is prevalent in rowing as mentioned in the book *The Sculler at Ease*:

> "The fallacy is in thinking that one should try to produce back splash, the sure indication that the blade is ready to be pulled in to the water. From this

> misconception, it is easy to conclude that one should drop the blade in the water, and then pull [33]"

In addition, many coaches also preach "early roll ups." This technique is when the rower begins to slowly square the blade before the catch, usually as the handle travels past the knees on the recovery. The blade becomes completely square or perpendicular to the water as the rower reaches about 75% of the total distance to the catch. Early roll ups help a crew maintain their timing. It also helps ensure that the blade enters the water square. If the blade does not enter the water completely square, the blade will not set correctly in the water. The angle will cause the blade to travel deeper into the water. As the blade dives, the oar handle will travel upwards to the rower's head. This is called "catching a crab," probably named after the action a crabber's net makes as it enters the water.

The velocity of the boat and the inertial force of the water will make the handle nearly impossible for the rower to control. At best, the rower can keep the oar in front of his/her torso but the inertial force of the water will act on the blade and slow the boat. In the worst case, the oar handle will end up behind the rower pinning the blade to the gunwale, and the boat will stop as the oar is recovered. In some cases, the oar handle hits the rower and ejects him/her out of the boat. So coaches have good reason to be concerned about ensuring that the blade is square well before the catch and is why some encourage back splash. The question remains: Is it worth the risk in a competitive boat?

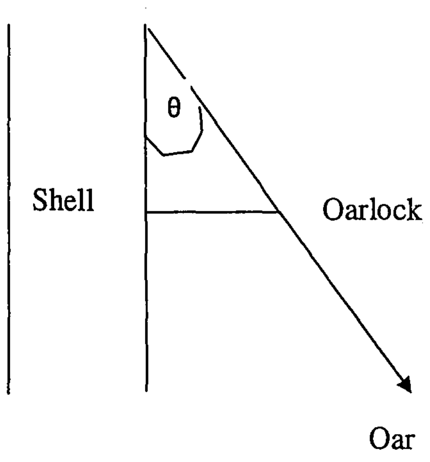


Figure 32: Description of Catch Angle (θ)

Macrossan and Macrossan attempt to answer this question [34]. As far back as 1925, it was realized that gravity does not supply enough acceleration to insert the blade fast enough to provide an efficient catch. Elite rowers have been measured inserting the oar at a rate of 11.2 radians per second, almost 6 radians per second faster than gravitational force alone. It was also noticed that these elite rowers do not drop the blade into the water at a 90° angle. A good rower will "row-in" at a slight angle to the farthest point reached on the recovery. Macrossan and Macrossan define the "row-in" angle as the angle between the point when oar reverses direction during the recovery (going from traveling towards the bow to traveling towards the stern) and when the oar blade contacts the water [34]. This is defined as

$$\varphi = \theta_{\max} - \theta_c \qquad (42)$$

Where θ_c is the angle at which the oar makes contact with the water. The typical values for φ are around 3° to 5° for elite scullers. It is important to note here, that φ is usually different for both oars the sculler uses [34].

Using data collected from on-water testing, Macrossan and Macrossan calculated the average back splash force to be about 94 Newtons per blade under best case scenarios (i.e. calm water, and the rower making no other mistakes). This force results in a 2.2% loss in average boat speed or about 44 meters over a 2,000 meter course compared to a boat that is rowing cleanly with the proper row-in angle [34]. In addition to this loss of speed, other problems will arise from back splash. For instance, any rower (other than the bow man) who generates back splash will splash the athlete behind him/her. As well as being distracting, the splash will cause the rower's hands to become wet. It will then become more difficult to grasp the oar causing other technique issues.

Rowers and coaches can rest easy; there is a way of ensuring minimal or no back splash while rowing. In order to prevent this problem, the rower's oar must have an angular velocity such that the minimum angular velocity of the blade is parallel to the oar. Here the minimum angular velocity is

$$\dot{\varphi}_m = v / l * \sin(\theta) \quad (43)$$

Macrossan and Macrossan defined a constant called the catch factor, *C*, to help simplify things. Defined as

$$C = \varphi / \varphi_m \quad (44)$$

Thus when $C = 1$, it is perfect timing for the blade to enter the water without creating backsplash [34].

Rowing occurs much too fast for anyone to see this. Also, the crew members must look straight ahead to ensure timing and cannot turn their heads to look at the blade. How can a rower know that the oar is being inserted into the water properly? Cunningham, Macrossan, and Macrossan agree that a perfect catch will have either no splash or a minimal amount of splash on both the fore and aft side of the blade [33, 34].

5c. Effects of Rigging: Spread

The previous two ideas presented have a dramatic effect on rowing performance. Coaches sometimes make changes to the boat hoping for gains in speed and virtually do nothing to affect the overall velocity of the boat. On regatta day, a spectator will see coaches and coxswains surrounding the boat making adjustments and tweaks like bees building a hive.

One thing that is adjusted constantly on race day is spread. Spread is the distance from the center line of the boat to the pin that supports the oarlock (see Figure 33). On most riggers, the pin can be adjusted one to two inches inboard or outboard. Obviously, moving the pin in either direction will affect the load the oar moves. The question is how much?

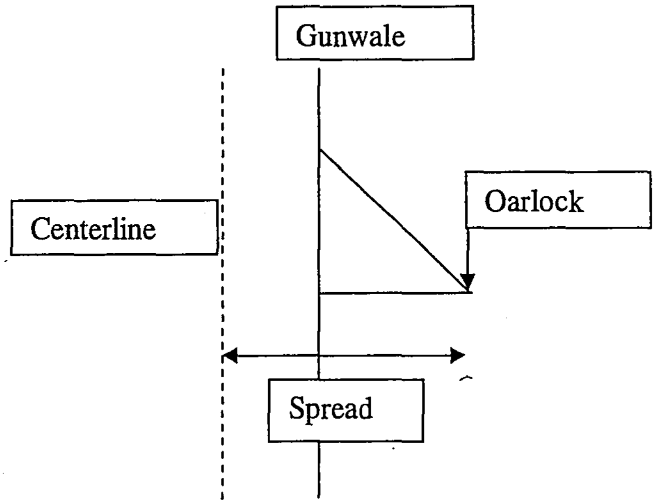


Figure 33: Visual Description of Spread

Mike Davenport wrote *The Nuts and Bolts Guide to Rigging* [35], which has been called the "Bible" of rigging by coaches. He refers to the adjustment of spread as "the most important adjustment you'll make in rigging" and "the most critical ingredient of the 'gearing'." According to Davenport, moving the pin inboard or out will cause the "greatest" change in leverage. However, Davenport does not use mathematical justification for his reasoning. It is simply stated that these adjustments are important in changing the load one's crew will carry while rowing.

The rowing community has followed in suit. Smaller boats tend to use larger spreads in relation to the size of the shell than larger boats since larger boats are subject to a smaller load since they are traveling faster. In addition, women tend to row with larger spreads than men since traditionally men are stronger.

Dr. Atkinson [36] proposes a logical geometric argument on his website as to why adjusting the spread has limited value for scullers, and has hardly any affect on sweep rowers whatsoever. A typical example will help explain his argument here. Using the average reach for a rower, a typical handle length, and the conventional spread for a heavy weight men's four a final catch angle of 37.667° is calculated. By moving the spread in by four centimeters (this is typically all that standard rigging will allow), coaches hope to get a smaller catch angle resulting in a heavier load. However, this achieves a final catch angle of 36.862°. Changing the spread by the most distance allowed by the rigging gave the rower only 0.805° more catch. This is less than a one percent change in the total radial distance the oar covers during the stroke.

5d. Oar Bending

Whether the spread is adjusted perfectly or not, the oarlock does play another important role in rowing. It is integral in creating a bending moment on the oar. In general, the force of the water on the blade combined with the effort exerted by the rower on the handle creates enough force to cause the shaft of the blade to lose its shape. This is true for both wooden and composite shafts.

Oar manufacturers like Dreher and Concept 2 produce three styles of stiffness for their shafts: low, medium, and high. Typically, these variations are based on the deflection obtained when a 10 kilogram load is applied at a set distance on the shaft. However, oar manufacturers differ in their definitions of stiffness. On average, Macrossan states that a medium stiffness oar shaft deflects a maximum of about 5.3° throughout the drive at a rate of over 40 strokes per minute (racing pace) [1].

Unlike changing the spread, the magnitude of this bending may be critical due to how it affects the blade's path in the water. When the oar is at the square off point, the shaft bends causing the blade to lag behind. The blade continues to cause a pinching force on the boat because of its lag at the square off point [1]. This reduces the efficiency of the blade. Macrossan proposes the following efficiency equation to include the bending of the oar

$$\eta = V/(wl) * \sin(\theta - \lambda) \quad (49)$$

Where λ is the angle between the blade force and the force acting normal to the face of the blade (see Figure 34), V is the velocity of the boat, w is the oar rotational speed, and l is the outboard length of the oar. Ideally, the oar would not bend at all causing the sine section of the equation to become larger and efficiency to increase. Bending causes the average efficiency to drop by 4% for a typical sweep oar [1].

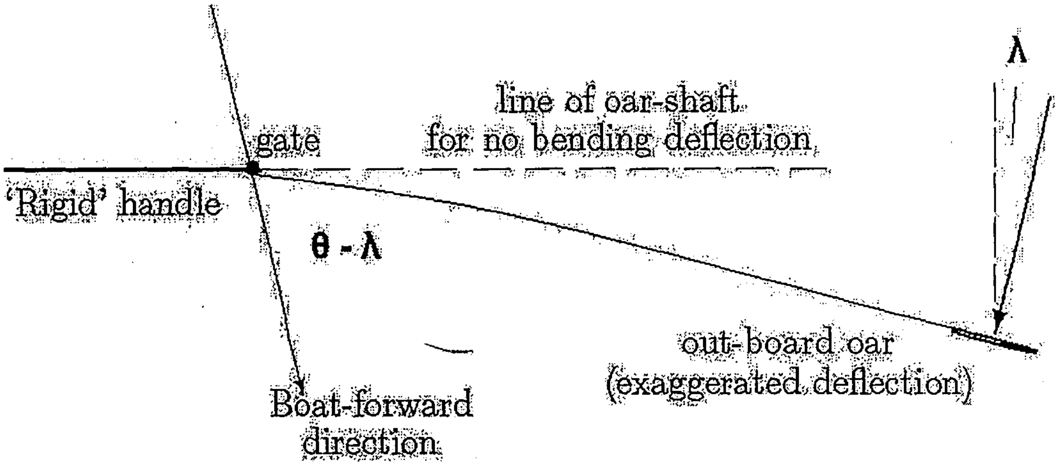


Figure 34: Bending Angles [1]

As mentioned in Chapter 4, a loss in efficiency is not always detrimental to the speed of the boat. Here, efficiency is crucial to the boats speed. Macrossan calculated an average propulsive power of a rigid oar to be 20 watts greater than that of an oar that bends to the above angle (this is about a 5% loss in power overall) [1].

This concept is also not without controversy. Macrossan studied only the oar up to and including the square off point. He did not explore further. When an oar shaft bends, it eventually rebounds later in the stroke. According to Atkinson [6], the oar is almost completely elastic and thus all the stored energy in the beginning of the stroke is released later in the stroke. Little energy is lost to heat, if the shaft is well manufactured. Thus, little momentum is lost due to the flexibility of the shaft [6].

Bending may provide an advantage for the rower. At the catch, the weight of the load is placed proportionally (through gearing) onto the rower. The rower carries a good part of this load on his back. Bending of the oar may help delay and distribute this load and ease the strain on the back muscles.

Atkinson fails to mention the effect of bending on blade force. As Macrossan showed, bending will change how the blade is angled during various parts of the drive. When a blade bends, it is no longer perpendicular at the square off point which is also the most efficient and most powerful part of the drive (see Chapter 4). Thus, a loss of momentum might be observed. In addition, the blade will follow through and release the stored energy later in the stroke. Here are two problems. First, the blade is now traveling through turbulent waters where it is more likely to experience slippage. The more power that is added at this point of the stroke, the more the blade slippage will increase. Secondly, the majority of the power is not being applied at the square off point where the velocity vector of the boat and the blade force are parallel. The power is being delayed due to the bending until the oar has passed this point. The force vector and the velocity vectors later in the stroke are no longer parallel. This results in a pinching force and some of the energy being wasted and not applied to the boats forward momentum.

Chapter 6: Rowing Out of the Wake

A spectator once asked a coach, "Why do you have your team train so hard? It looks easy." The coach just chuckled. The beauty and grace of rowing masks its true nature: chaos. By making it look easy and elegant, the rower creates an illusion. If that spectator could sit in the coxswain's seat and "go behind the scenes" of a men's heavyweight eight (traditionally the fastest boats at regattas), he/she would have felt this for himself. Rowers do not keep the boat in motion; they accelerate it with an inspiring use of harnessed raw power, making rowing an engineering pursuit. From an outsider's point of view, rowing should be based on a simple set of equations any second year physics student could solve. In reality, the chaos of turbulent flow around the oar and shell combined with complex differential equations used for modeling velocity, efficiency, and power makes rowing intriguing to many engineers. The engineers who have approached this topic have become artists in their own right, masking the complexity of the physics in eye catching equations. While the equations may look simple, supplying the data to solve them is the real trick.

Through the work of scientists such as Macrossan, Kleshnev, and Atkinson, some of the secrets behind rowing have been revealed. The question remains: "Where to go from here?" The answer is simple: Make the boat go faster. However, the path is more complex.

There are many boat companies that state their shells are the fastest, such as Vespoli, Empacher, Durham, Hudson, and Kaschper. But what is the significance of their claims? Each year, these companies introduce new models even though hull drag plays only a minor role in diminishing rowing's efficiency. Since FISA mandates a minimum boat weight, it is doubtful that the differences among these models can be great. The manufacturer's best offer is hull stability, thereby enabling the crew to apply power to the oar.

The best opportunity for improving shell velocity is in oar design, but astonishingly there are only a few mainstream oar manufacturers (Concept 2, Dreher, and Croker). As discussed in Chapter 4, blade slippage makes up for over a 5% loss in rowing's efficiency. New designs for the blade could help eliminate some slippage. Since air and water share similar properties of lift, ideas for these new possibilities could be gleamed from the aerospace community where more studies have been done as a result of its popularity and funding

One idea that shows possible applications is the use of airfoils on the end of wings to increase lift in aircraft. If oar manufacturers attached foils to outside edge of blades, rowers could discover an increased lift of the blade. This would then push the vortices resulting from the water shedding away from the oar thus, reducing slippage. This follows a similar design logic used by the Concept 2 Vortex Edge described in Chapter 3. Theoretically, this foil would not interfere with the extraction of the oar out of the water if the blade is removed still square, as is standard technique. However, theory and practice are two entirely different matters. For example this device could cause the oar to carry more of a load which would be detrimental to the rower's back and stamina.

Further development in blade testing needs to be made in order to test new theories like the one above. Current blade testing is operating below the tolerances of the equipment used. This makes the results questionable. Concept 2 has acknowledged this and recommends crews test their own oars. The LMF has invented a new way of looking at water flow over plates. These simulations might push oar design to the next level because what was once done on the test range in hours could be accomplished on a computer in minutes.

But what is a coach to do, outside of retrofitting his crew with experimental gear? The current trend in rowing is to row at higher stroke rates. While the crew sacrifices efficiency, the higher rate limits the speed oscillations and keeps the shell at a more constant velocity. In addition to this being more efficient, the rowers do not have to carry as heavy a load although they do take more strokes. Over a six minute row (a decent 2000 meter sprint time), a crew rowing at 36 strokes per minute will only take 36 more strokes than a boat rowing at 30 strokes per minute. However, it was also shown that power increased by over 150 Watts per rower by increasing the rate from 30 to 36 [18].

In order to keep these high stroke rates, the velocity of the drive increases. This could result in a crew member "jumping off the foot stretchers," meaning that he/she is applying maximum force on the oar at the catch. This is not beneficial as mentioned earlier. The better course of action is to have to rower initiate the drive and build force. As the boat begins accelerating, the rower should steadily and quickly reach peak output. This output should be maintained as long as possible during the drive to ensure that boat maintains acceleration and the blade's drag does not slow the boat down. Focus should be on the legs but the torso and arms should not be neglected. The legs provide 45% of the power applied to the shell while the back and arms add the remaining 55% [18].

In general rowing practice, each body part acts almost independently of each other. Rowers are taught to start with their legs, then initiate their backs, and finally finish with their arms. Theoretically, it would be beneficial to emphasize more power in the middle of the drive by initiating the arms and back before the legs are pressed down may increase speed. A drawback to this style may be found if early initiation of the arms and back resulted in less energy output by the rower.

Other more drastic techniques, such as asynchronous rowing, have been ignored by the rowing world. It is possible there is a faster way of moving a boat. The movable rigger was introduced a few decades back and crews raced with them. This new rigging proved to be faster than current stationary rigging. However, FISA decided that these new riggers did not fit in the sport of rowing. The movable rigger has not been forgotten. Virus boats (www.virusboats.com) produce a variety of shells that come with movable foot stretchers and rigging which allow the machine to move around the rower. Since rowing has been around so long, it is hard to say if traditionalists will ever adapt to new mechanical adaptations, then again people thought the moving seat would never become common place.

Outside of the rower's performance, the coach also has control of the equipment. As pointed out in Chapter 5, some changes have little effect but there are ways of increasing the leverage of an oar. If coaches and rowers want to change the load that is carried through out the stroke, adjustment of the inboard and outboard is most important. This has the biggest effect on gearing and will add more load or release load depending on the preference. Since the inboard can only be adjusted a certain amount due to design restrictions and the physical limitations of the rower, it is probably best to adjust the inboard for comfort and to ensure the best physiological performance. To adjust the load, the oar collar should be adjusted to provide the desired amount of outboard.

The desire to be faster has been a great motivator to man whether on land, air, or water. With a new lust for aerobic training, rowing is becoming more popular due to its low impact and heart healthy style of exercise. This will lead to more engineers taking a closer look into the sport. As for rowers, St. Mary's College Varsity Crew member ('00) Jeff Carter captured our feelings best when he said "We may show love to others on the outside, but the river is the blood that runs through our hearts."

References:

1. Macrossan, M. N. "The Direction of the Water Force on a Rowing Blade and its Effect on Efficiency." University of Queensland, Mechanical Engineering Report No. 2008/03, April 2008
2. http://www.atm.ox.ac.uk/rowing/physics/
3. Kleshnev, Valery *Rowing Biomechanics Newsletter* 7 (71) February 2007 pg 3
4. Celentano F., Cortili G., et al "Mechanical Aspects of Rowing." *Journal of Applied Physiology* **36** (6) June 1974 pp. 642-647
5. Caplan, Nicholas and Gardner, Trevor "Modeling the Influence of Crew Movement on Boat Velocity Fluctuations Druing the Rowing Stroke." *International Journal of Sports Science and Engineering* **1** (03) 2007 pp. 165-176
6. http://www.atkinsopht.com/row/rowrpage.htm
7. http://www.concept2.com/us/oars/default.asp
8. Beaton, Brendon "Lift and Drag on the Blade of a Rowing Oar" University of Western Ontario 11 October 2002
9. Dimakos, Jim "Oar Blade Design: Materials and Manufacturing Processes"
10. Dreher, James "New Blade Shapes Part I" www.durhamboats.com 29 January 1997
11. Dreher, James "New Blade Shapes Part II" www.durhamboats.com 08 January 1999
12. Dreher, James "Latest Development in Dreher Oars and Sculls, the Apex Blade Design" www.durhamboats.com 10 November 2000
13. Dreher, James "New Blade Shapes Part III" www.durhamboats.com 01 January 2000
14. Dreher, James "New Blade Shapes Part V" www.durhamboats.com 12 December 2003
15. Brearley, Maurice and de Mestre Neville "Improving the Efficiency of Racing Shell Oars" *The Mathematical Gazette* **84** (501) November 2000 pp. 405-414
16. Leroyer, Alban et. al. "Experimental and Numerical Investigations of the Flow Around an Oar Blade" *Journal of Maritime Science & Technology* **13** 2008 pp. 1-15
17. Mohseni, K., Shkoller, Kosovic, B., Marsden, D., Wray, A., & Rogallo, R. "Numerical Simulations of Homogeneous Turbulence Using Lagrangian-Averaged Navier Stokes' Equations" Center for Turbulence Research Proceedings of the Summer Program 2000 p. 272
18. Cabrera, David and Ruina, Andy "Propulsive Efficiency of Rowing Oars" Cornell University 13 February 2006
19. Kleshnev, Valery "Propulsive Efficiency of Rowing" Australian Institute of Sport, Canberra, Australia www.biorow.com
20. Kleshnev, Valery "Stroke Rate vs. Distance in Rowing during the Sydney Olympics" Australian Institute of Sport *Australian Rowing* 24(1) April 2001 pp 18-22 www.biorow.com

21. Macrossan, M. N. and Macrossan, N. W. "Energy Efficiency of the Rowing Oar from Catch to Square-off" University of Queensland, Mechanical Engineering Report No. 2008/05
22. Kleshnev, Valery "Facts. Did you know that…" *Rowing Biomechanics Newsletter* **2** (1) January 2002 pg. 1
23. Kleshnev, Valery "Estimation of Biomechanical Parameters and Propulsive Efficiency of Rowing" Australian Institute of Sport, Biomechanics Dept. October 1998 www.biorow.com
24. Brearley, M. N., de Mestre, N. J., and Watson, D. R. "Modelling the Rowing Stroke in Racing Shells" *The Mathematical Gazette* **82** (495) November 1998 pp. 389-404
25. http://www.goodfelloweb.com/centipede/
26. Rowing Clip dated 01 January 1931 No. BGT407141226 0 Copyright: GAUMONT GRAPHIC NEWSREEL (REUTERS) http://www.itnsource.com/shotlist//RTV/1931/01/01/BGT407141226/?s=rowing
27. Kleshnev, Valery *Rowing Biomechanics Newsletter* **7** (70) January 2007
28. Kleshnev, Valery "Power in Rowing" Australian Institute of Sport pp. 1-4
29. Kleshnev, Valery *Rowing Biomechanics Newsletter* **6** (66) September 2006
30. Email from Dr. Kleshnev to the Author dtd. 6 October 2008
31. Kleshnev, Valery *Rowing Biomechanics Newsletter* **6** (66) September 2006
32. http://www.atkinsopht.com/row/asynchro.htm
33. Email from Dr. Atkinson to the Author dtd. 19 June 2008
34. Cunningham, Frank *The Sculler at Ease* Avery Press. Boulder, CO 1992 pp. 98, 132
35. Macrossan, M. N. and Macrossan, N. W. "Back-splash in Rowing-shell Propulsion" Mechanical Engineering Report No. 2006/07 University of Queensland 6 June 2006
36. Davenport, Michael *The Nuts and Bolts Guide to Rigging* Sport Work Inc. Church Hill, MD 2002 pp. 184, 197, and 203
37. http://www.atkinsopht.com/row/rigging.htm

Appendix A: Water Properties and Their Effect on Rowing

It is important to note here that water depth affects boat speed. Due to the friction of fluid flow over a surface, rivers flow faster deeper and farther from shore. In addition, the river will generate its own vertical shear if it is flowing (which most rivers do). The boat, also, generates a shear profile as it moves through the water. Moving upstream results in a subtraction of these two shears and downstream the sum. This is due to the boat travelling slower upstream with respect to land. As mentioned before, the faster the boat moves the greater the drag. Here, the depth of the water comes into play. In shallower water, the shear force becomes bounded by the bottom of the river. This bounding causes the forces of the shear to become a more effective force in slowing the boat. The critical depth for "unbounded" shear force is approximately one meter. For this reason, all FISA race courses have a minimum depth of two meters. [2]

Other properties of water that affect boat speed are its salinity and temperature. Fresh water is less dense than salt water. A boat's hull sits higher in salt water than fresh resulting in a less wetted surface. In addition, the less dense fresh water results in greater oar slippage. From an initial look, it appears that rowing in salt water would result in faster times. It turns out that the density of fresh water creates less skin friction and results in the boat cutting through the water faster. This theory of density can be transferred to water temperature. At lower temperatures, water is denser causing it to act similar to salt water. But again, the less dense hotter water results in faster race times. This is because the viscosity of warmer water is significantly lower than that of cold water. Noticing Figure 7, water temperature makes a significant impact in boat speed. In addition, warmer water usually corresponds with thinner warmer air [6].

Water temperature, C	**0.0**	**10.0**	**20.0**	**30.0**	
Eight (8+), heavy men			Base		
Rating, 1/min	30.1	30.1	30.1	29.9	
Drive/return period ratio	0.562	0.551	0.546	0.537	
Average shell speed (m/s)	**5.663**	**5.736**	**5.791**	**5.864**	
Total rower power (Watts)	603	603	603	603	
System efficiency	0.540	0.539	0.537	0.538	
Oarblade efficiency	0.799	0.802	0.804	0.807	
Absolute blade slip (m)	0.540	0.540	0.530	0.521	
Time for 2000m (sec)	353	349	345	341	
Delta time (sec)	-8	-4	0	4	
Lengths in 2000m	**-2.5**	**-1.3**	**0.0**	**1.3**	
Shell length (m)			18.29		
Resistance factor, K (water, N-(s/m)^2) *	12.592	12.065	11.682	11.251	*Corr. wave & form
Resistance coefficient, Cf (ITTC '63 base)	0.00264	0.00253	0.00245	0.00236	
Wetted surface (m^2)	9.52	9.52	9.53	9.54	
Reynolds' number, Re (at Vavg)	5.80E+07	7.90E+07	1.00E+08	1.30E+08	

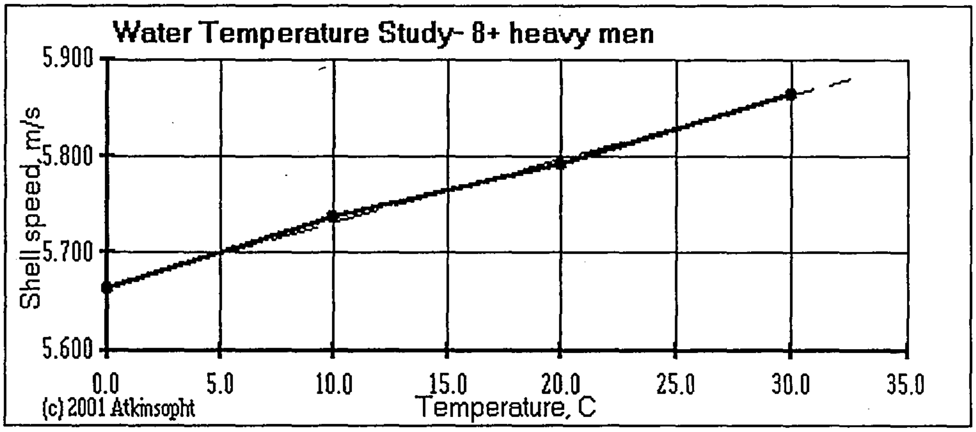


Figure 35: Men's 8 Velocity Compared to Water Temperature [6]

However, it should be noted that athletes also perform better in warmer temperatures because muscles are warm which leads to better flexibility and allows for greater delivery of oxygen.

The understanding gained through these studies on the physics of rowing should enable engineers to solve this riddle and would not only put their minds to rest but would help rowers propel the boat faster and aid in the understanding of the complex world of fluid dynamics.

Vita

Paul Conlin graduated St. Mary's College of Maryland in 2000 with a degree in Mathematics and another in Religious Studies. During his college career, Paul became an avid rower. He continued his pursuit of engineering through the University of Idaho distance learning program. Paul is currently working with the U.S. Navy and the Swiss Air Force as a Systems Engineer on the F/A-18. As a systems engineer, he analyzes the structural fatigue of the aircraft and coordinates flight testing. During his tenure as a systems engineer, Paul has completed the requirements for a Master's of Science Degree in Mechanical Engineering at Lehigh University. Paul continues to row, compete, and medal. In addition, he has volunteered his time for the past 8 years to coaching the St. Mary's Crew team.

END OF
TITLE