Physics ATAR

Science Inquiry Skills Test 2019

Mark:	/ 48
=	%

Name: SOLUTIONS

TEACHER: JRM HKR

Time Allowed: 50 Minutes

Notes to Students:

1. You must include **all** working to be awarded full marks for a question.
2. Marks will be deducted for incorrect or absent units and answers stated to an incorrect number of significant figures.
3. **No** graphics calculators are permitted – scientific calculators only.

Effect of Oar Length on Rowing Performance

Rowing (see Fig 1.) is a challenging sport, and not just for athletes. It mixes physiology, mechanics, and fluid dynamics, so from a physicist's perspective, the sport is much more complex than the elegant movement of a rowing boat (also known as a shell) may suggest. Success in the support requires an effective biological system (the rower) and an appropriately designed mechanical system (the boat and oars) that use the rower's power efficiently and minimises drag force.

Figure 1 - *Rowers and a rowing boat (shell)*

Fundamentals of Rowing

The rower sits in the boat facing the stern and uses oars which are held in place by oarlocks to propel the boat forward (towards the bow) as shown in Fig. 2.

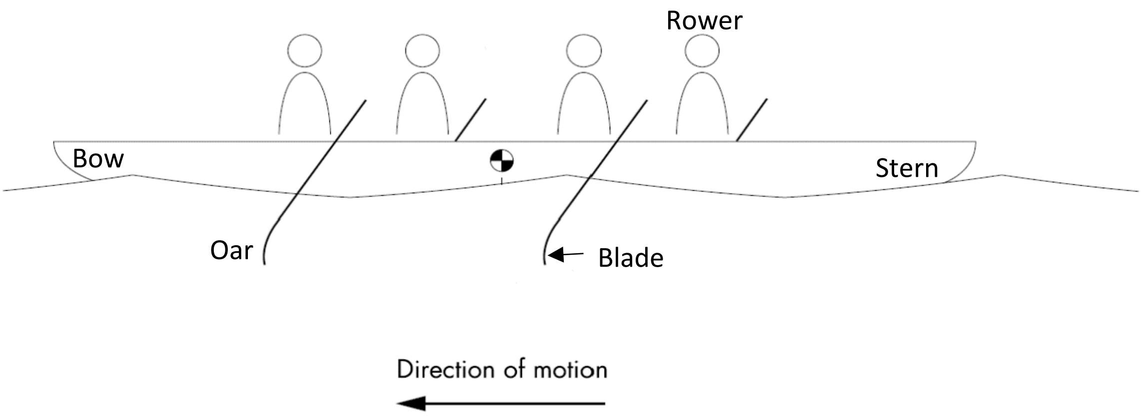


Figure 2 – *Rowing boat – indicating location of Bow, Stern and direction of motion of the shell.*

The oar plays an important role in the rowing system by transmitting the force, developed by the rower, to the blade. Joint movements generated by the rower result in movement of the rower with respect to the shell. This causes a corresponding movement of the oar handle that is resisted by the interaction of the blade and the water. By Newton's Third Law; as the blade pushes on the water, the water pushes on the blade – pushing the boat in the direction of the bow.

Boat and oar setups are shown in Fig. 3.

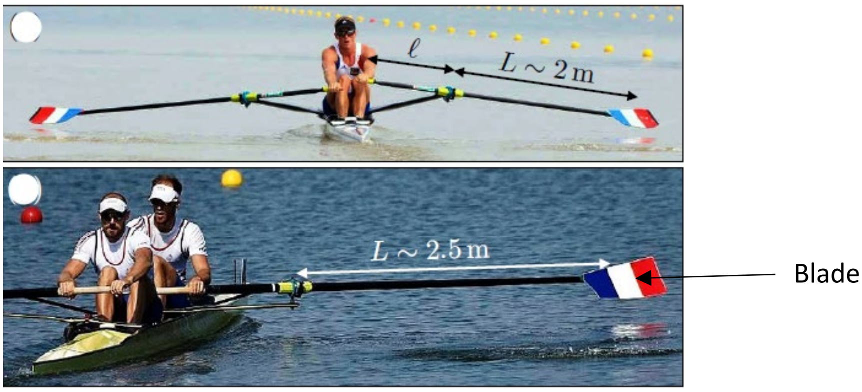


Figure 3 – *Rowing boats and oars – note the location of the blade of the oar.*

The goal of a rowing race is to travel a set distance in the shortest possible time. Therefore, maximum average shell velocity is critical to race performance. Average velocity results from the combined effect of the propulsive force generated by the biological system overcoming the drag forces acting on the mechanical system.

The rowing stroke is divided into two phases: a propulsive phase - when the blade is in contact with the water and a recovery phase – when the blade is not in contact with the water. A good rowing stroke corresponds to a force profile as constant as possible during the propulsive phase.

The handle force during **one** stroke as a function of oar angle for two top-level

French rowers (Edward Jonville and Augustin Mouterde) is shown below in Fig 4.

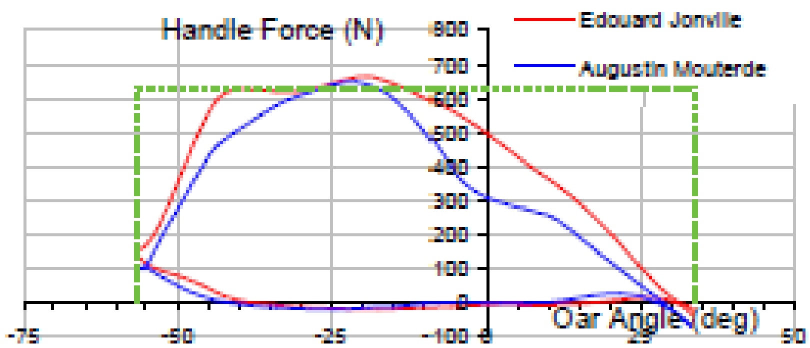


Figure 4 - *Handle force during one stroke for two top-level French rowers.*

(a) According to the criteria of constant force profile – state which of these rowers, Jonville or Mouterde exhibits the greatest consistency in their force profile.

(1 mark)

Jonville

The external forces acing on the rowing oar during the drive are shown in Fig. 5

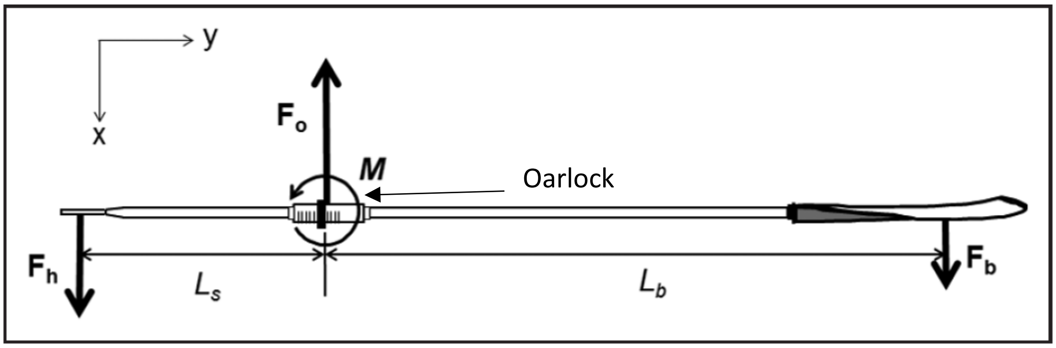


***Figure 5 -** Forces acting on the rowing oar during the drive.*

F_h represents the effort applied by the rower to the handle (handle force), **F_b** is the load on the blade and **F_o** is the normal force at the oarlock. It can be assumed that the rowers move the handles on both sides of the boat evenly and apply forces symmetrically on each handle so that all lateral forces in the y-direction cancel each other out. The lines of action, therefore, are in the x-direction, parallel to the boat's main motion.

(b) Write an equation to show the sum of forces on the oar.

(1 mark)

$\sum Fx = F_o - F_h - F_b = 0$ or $F_o = F_h + F_b$

The force on the blade is generated by the rower's movement of the handle relative to the shell by exerting force on the oar handle. The rower 'pulls' on the handle, which pivots around the oarlock, causing a torque that turns the oar around this point of the shell (the axis of the oarlock). The resulting movement of the blade in the water creates the propelling force that acts on the total system. In general the forces F_h, F_b and F_o are not always perpendicular to the oar shaft, however, it can be assumed that these forces act at 90° without affecting the general nature of conclusions made in this assessment.

The support moment arm (L_s) is the perpendicular distance between the points of application of the force vectors F_h and F_o and the beam moment arm (L_b) is the perpendicular distance between F_o and F_b.

(c) Write a formula for the net torque on the oar using the oarlock as the pivot, assuming that the motion of the stroke is in equilibrium (not accelerating).

(2 marks)

$\sum \tau = (F_b)(L_b) - (F_h)(L_s) = 0$ or $F_bL_b = F_hL_S$

As the sport of rowing had evolved, the blade area and design, and the length of the oars has changed, as shown in Fig. 6.

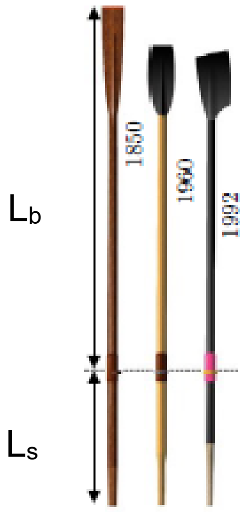


Figure 6 - *The evolving nature of rowing oars.*

It has been theorised that a shorter L_b could be more effective in rowing, making for faster rowing times, independent of the force on the handle set by the rower.

(d) State why this could be the case making reference to the equation derived in (c) and any other relevant laws of Physics.

(4 marks)

- F_b is what is pushing on the water - which will cause the water to push back on the boat, making it move. As per Netwon's 3rd Law.
- And L_s has not changed in the evolution of the oar
- $F_b = F_h L_s / L_b$
- To increase F_b is to decrease L_b.

Effect of Oar Length on Rowing Performance

Two experimental studies have been conducted to investigate the effect of oar length on rowing performance. One using human participants and the other using rowbots (rowing robots).

Study One – Human Participants

In the study conducted by Laschowski, B. et al (2015) four female rowers were recruited from the University of Western Ontario varsity program. The rowers gave informed written consent to participate and the work was approved by the University of Western Ontario research ethics board. Two sets of oars of different stiffness were investigated at three different lengths. The different outboard lengths (L_b) of oars ranged from 1.79 to 1.83 m. The inboard length (L_S) was fixed at 0.87 m.

Each rower performed a self-directed warm-up. The rowers were started from a zero boat velocity relative to the water, the rowers used approximately 100 m to accelerate to their individual race pace and then rowed an additional 200 m at a constant race pace for data collection.

Each rower completed 6 trials and each trial was used to test a different oar length and stiffness, as shown in Fig. 7. The experiment was single-blinded, whereby the configurations of the oar were unknown to the rowers. The six configurations were tested in a different order for each rower. To minimise fatigue, the rowers had 12 ± 3 minutes to rest between trials.

Figure 7 – *Six oar configurations tested*

Code	Stiffness	Total length (m)	Outboard length (m)
M2.66	Medium	2.66	1.79
M2.68	Medium	2.68	1.81
M2.70	Medium	2.70	1.83
ES2.66	Extra-Soft	2.66	1.79
ES2.68	Extra-Soft	2.68	1.81
ES2.70	Extra-Soft	2.70	1.83

(e) State the independent variables being investigated.

(2 marks)

- Stiffness of the oar
- Oar length

(f) Discuss the effect on validity of having more than one independent variable tested at the same time.

(2 marks)

- Cannot be sure which variable is having an effect on the boat speed
  OR
- by how much each variable affects the boat speed

- This reduces the validity of the conclusions drawn.

The experimenters found that there was a strong negative correlation between oar length and 200 m performance for rowers a) and b). Rowers c) and d) showed a mild positive correlation between oar length and 200 m performance. The handle force (F_h) is shown for each of these rowers in Fig. 8.

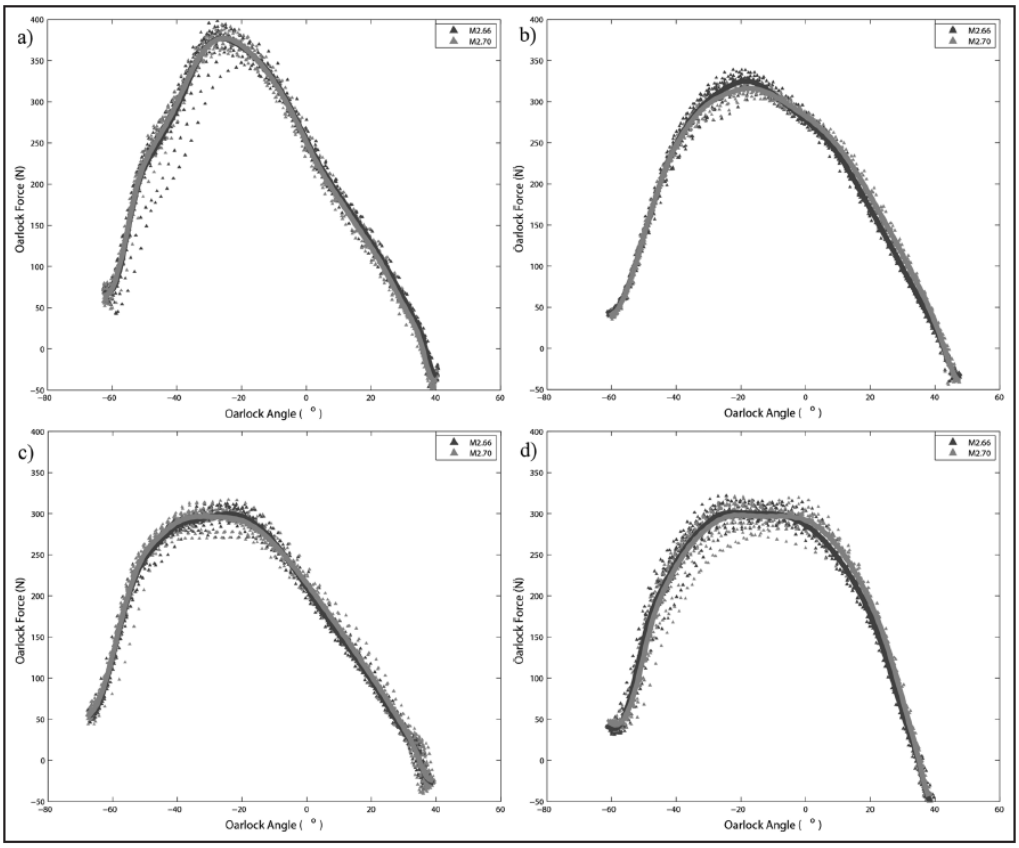


Figure 8 – *Handle Force vs oarlock angle for rowers a), b), c) and d).*

(g) State which two rowers are the more skilled and explain your choice

(2 marks)

- c) and d)
- They have a more consistent force profile through the propulsive phase

(h) Based on the findings of the investigation, what can be said about the effect of oar length on the 200 m performance time based on skill level of rower from this investigation.

(2 marks)

- The shorter oar length has a greater effect on 200 m performance time for the less skilled rowers.
- This was shown by the strong negative correlation between 200 m time and oar length for these rowers (i.e as the oar length decreased, the 200 m time increased).

Study Two – Rowbots

In the study conducted by Labbé, R. et al (2019), the researchers designed and manufactured a robot rowing boat with imposed propulsive force. They used a wooden mold based on a real rowing shell at a scale of 1/10th to make a fiberglass rowing boat with 4 robot rowers with one oar each, as shown in Fig. 9a.

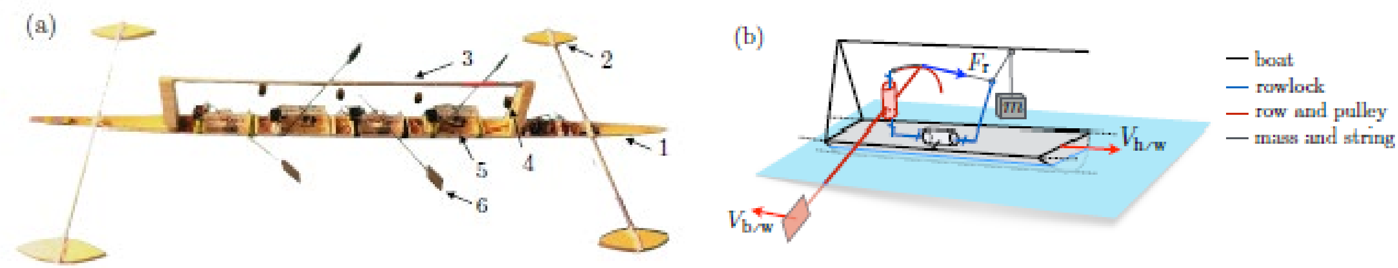


Figure 9 – *The rowboat apparatus (a) with suspended mass (b) to simulate F_H applied by rowers.*

Constant force during the propulsive phase was ensured through a pulley-mass system. Each row was linked to a pulley centered at its rowlock (oarlock), as shown in Fig. 9b. A suspended mass was connected to the pulley through a string by that setting the row in motion at constant force F_R = mg. Frictional losses in all connections were neglected.

The angular travel of the row was fixed to θ = 90°. The recovery phase and the blade flips were ensured by two servomotors and position sensors connected to an Arduino board. The masses are suspended to a unique support and four polystyrene floats were added to ensure the stability of the boat.

The experiments were performed at the Ecole Polytechnique indoor swimming pool. The recovery phase was set to a constant value T = 1.3 s, video recorded the model boat rowing over a 25 m distance for four different row lengths, with corresponding aspect ratios spanning from α = 5 to α = 8 ($\alpha = L_b/L_S$). The blade dimensions were length = 7.0 cm and height = 4.7 cm.

The resisting drag force F_R on the oar is given by the formula below.

$$F_R = \frac{1}{2}\rho S C_d \mathrm{v}^2$$

Where;
ρ is the density of water (9930 kg/m^3)
S is the cross-sectional area of the blade relative to the water (m^2)
C_d is the drag coefficient (dimensionless)

Labbé, R. et al extended the lever model (page 4) to consider oar dynamics and boat propulsion at constant force. To ensure their extended theoretical model was consistent with their experimental results, they checked their calculated values for drag coefficient (C_d), from their experimental results, against literature values.

Values for the velocity of the blade using different values of suspended mass for a fixed length of oar are given in the table below. The uncertainty in the measurement of the velocity of the blade is 1.5%.

m (± 0.005 kg)	v (ms^{-1})	**F_R (± 0.05 N)**	**v^2 ($x10^{-2}$ m^2s^{-2})**
0.020	0.043	**0.20 (2.s.f)**	**0.18** ± 0.01 (2.s.f)
0.040	0.086	**0.39 (2.s.f)**	**0.74** ± 0.02 (2.s.f)
0.060	0.115	**0.59 (2.s.f)**	**1.32** ± 0.04 (3.s.f)
0.080	0.139	**0.78 (2.s.f)**	**1.93** ± 0.06 (3.s.f)
0.100	0.158	**0.98 (3.s.f)**	**2.50** ± 0.08 (3.s.f)
0.120	0.177	**1.18 (3.s.f)**	**3.13** ± 0.09 (3.s.f)

(i) Manipulate the data in the table as required to plot a linearised graph of drag force with respect to velocity squared, including any uncertainties present.

(8 marks)

-1 mark for: Sig fig error for F_R
Sig fig error for v^2
Decimal place error for F_R and v^2
Absolute error for F_R placed in rows (absolute error must be in heading)
Absolute error of v^2 not 3% (must be doubled as v^n)

(j) Plot a graph of **F_R vs v^2** on the graph paper provided.

(5 marks)

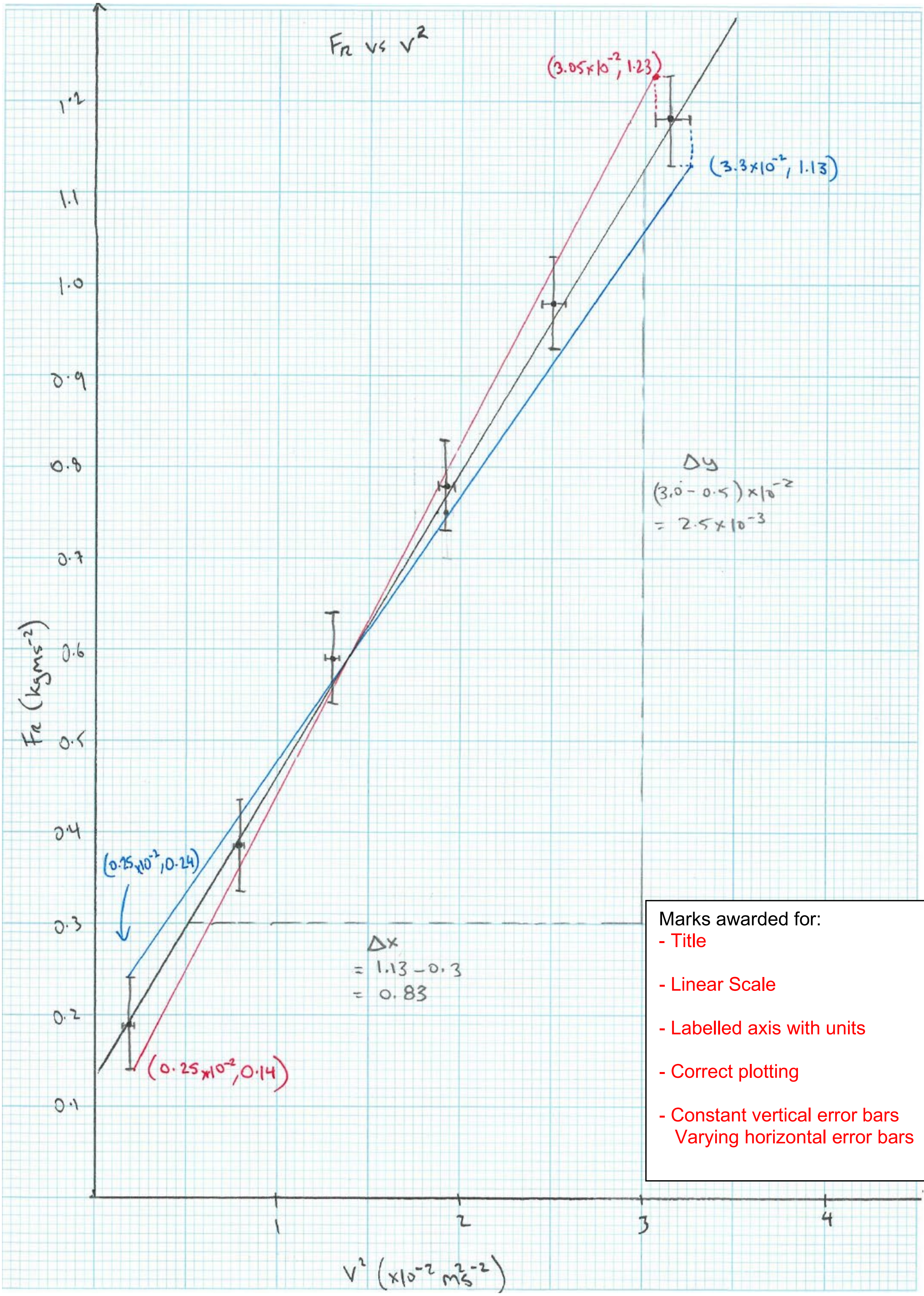
(k) Calculate the gradient of the graph, showing all working necessary.

(3 marks)

$m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{1.13 - 0.3}{(3.0 - 0.5)\,x10^{-2}} =$ 33 kg m^{-1} (2 s.f.) (allow $Nm^{-2}s^2$) (allow 3 sig fig)

(1/2) (1/2) (1) (1 mark for triangle on graph)

Excel gives L.S.R. of 33.2. Allow 31 – 35 kg m-1 (± 5 %)



Marks awarded for:

- Title
- Linear Scale
- Labelled axis with units
- Correct plotting
- Constant vertical error bars
  Varying horizontal error bars

(l) Use the gradient of the graph to calculate the drag coefficient of the oar blade.

(3 marks)

$\frac{F_R}{v^2} = \frac{\rho S C_D}{2} = 33$ (1)

$C_D = \frac{33\ (2)}{9930\ (0.07 \times 0.047)}$ (1)

= 2.0 (1)

(m) Using the error bars, draw a maximum and minimum line of best fit and hence, calculate the maximum and minimum gradient. Using the gradients, state the magnitude and percentage uncertainty of your gradient.

(6 marks)

lines of best fit drawn on graph (1)

*for full mark, line of best fit must go to corner of rectangle formed by vert and horiz bars, not to top of vert only. Maximum ½ mark if this is done.

$m_{max} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{1.23 - 0.14}{(3.05 - 0.25) \times 10^{-2}}$ = 38.9 = 39 kg m^{-1} (2 s.f.) (1.5)

$m_{min} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{1.13 - 0.24}{(3.3 - 0.25) \times 10^{-2}}$ = 29.1 = 29 kg m^{-1} (2 s.f.) (1.5)

Magnitude = range of gradients / 2 (1)
= (39-29) /2
= ± 5 Error d.p. must be same gradient stated in (k)

%unc = ± $\frac{5.0}{33}$ x100 = 15 % (2 s.f.) (1)

(n) Using your answer from (m), calculate the absolute uncertainty for the drag co-efficient of the oar blade.

(2 marks)

C_D = 2.0 ± 15 %

= 2.0 ± $\frac{15}{100} \times 2.0$

= 2.0 ± 0.3

Error must be expressed to same d.p. as measurement stated in (l)

(o) State if the graph indicates that there is any type of error present in this data. Explain your reasoning.

(3 marks)

- Systematic error
- Velocity should be zero for zero force (as there is no movement, hence no drag).
- The Y-intercept indicates that there is a systematic error in the measurement of the velocity (i.e a velocity reading when F = 0)

(p) The literature value for C_d for a blade with the given dimensions is 1.9. Calculate the percentage difference between this value and the measured value from l.

(2 marks)

$$\text{Percentage} = \frac{\text{measured} - \text{accepted}}{\text{accepted}} \times 100 \qquad (1/2)$$

$$= \frac{2.0 - 1.9}{1.9} \times 100 \qquad (1/2)$$

= 5.3 % above accepted. (1)

END OF TEST

Acknowledgments

A Baudouin and D Hawkins, 2002, *A biomechanical review of factors affecting rowing performance,* British Journal of Sports Medicine

Labbé, R., Boucher, J-P., Clanet, C., & Benzaquen, M. *Physics of Rowing Oars*

Laschowski, B., Nolte, V., Adamovsky, M. & Alexander, R., *The effects of oar-shaft stiffness and length on rowing biomechanics*, Proc IMechE. Part : J Sports Engineering and Technology. 2015, 229 (4), 239-247