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Procedia Engineering 00 (2013) 000–000

Procedia Engineering

www.elsevier.com/locate/procedia

The 2014 conference of the International Sports Engineering Association

Race-time prediction for the Va'a Paralympic sprint canoe

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Abstract

The 2016 Paralympic Games in Rio de Janeiro will see 200m sprint canoe events for the first time, using the Va'a class. The aim of this study is to predict race times for the Va'a over a 200m sprint event, through simulation of the hydrodynamic resistance of the hull (with outrigger) and the propulsion provided by the athlete. Such a simulation, once suitably validated, allows investigation of design and configuration changes on predicted race performance. The accuracy of the simulation is discussed through a comparison to times recorded for an athlete over a 200m race distance.

Paralympic sprint canoe; race-time prediction; hydrodynamic modelling; race simulation

1. Introduction

The Va'a canoe dates back almost 4,000 years from the islands of South Asia where their use was recorded for seafaring to the Pacific Islands and Eastwards as far as Madagascar, as well as for fishing. In 2008 the sport was officially recognised by the International Canoe Federation, ICF, and has now been accepted as a new Paralympic sport to be introduced in the 2016 Paralympic games in Brazil as the V1 class (IVF, 2011).

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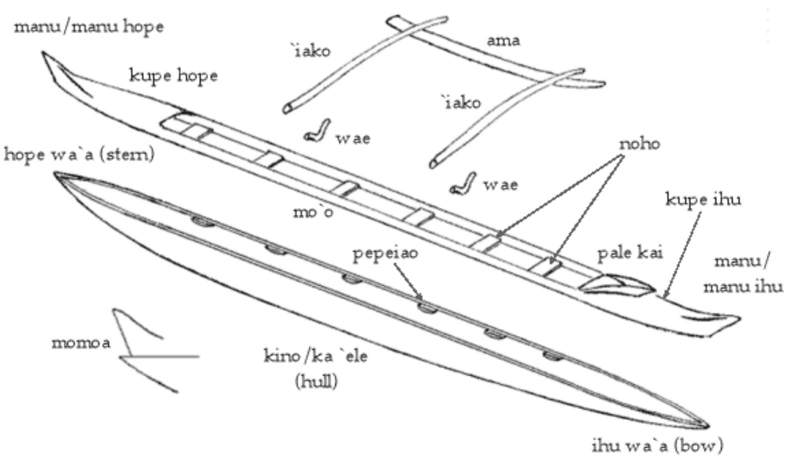
The modern racing canoe is made from lightweight composite materials, but still follows the traditional hullform that allows it to perform on both ocean waves and on flat-water as a sprint boat. The different parts of the canoe have kept their traditional names as outlined in Figure 1.

Figure 1: Parts of a Hawaiian outrigger canoe (Babineau, 2004).



The Va'a canoe is regulated by the International Va'a Federation, IVF, which has placed stringent requirements on the craft dimensions. However, the International Canoe Federation, ICF, have lifted these regulations for the V1 for the Paralympic games, instead prescribing a maximum length of 7.30m and a minimum weight of 12 kg. The position of the ama (outrigger pontoon) is not specified, save that the two iako (spreaders) must be separated by 'at least one seat' (ICF, 2011).

This paper aims to create a numerical race simulation tool for the Va'a canoe in order to predict race times. The simulation will therefore allow an analysis of the sensitivity of parameters on race time to be undertaken and ultimately may thus help in determining the best design and layout of the craft.

2. Methodology

2.1 Creation of Lines plan

In order to calculate hydrostatic and hydrodynamic quantities a lines plan of the hull is required. A table of offsets for the Va'a is thus recorded from an existing boat using a lines-fairing package (Cross-Whiter, 1998).

The main hull was raised after being dismantled from the ama and iakos. The locations of the iako attachments were measured from the nearest stations and the length of the ama was also recorded. The hull coordinates were obtained using a standard technique, through a combination of plumb lines and laser levels.

The recorded coordinates were used as 'templates' to create a network of bi-cubic patches to represent the surface of the hull in the lines fairing software, *ShipShape* (Cross-Whiter, 1998). The network of bi-cubic patches formed may be interpolated to give the hull coordinates (or offsets) for any location on the hull surface. Basic hydrostatic parameters such as hull wetted surface area and longitudinal centre of buoyancy together with hull form parameters (block coefficient, etc.) are obtained from the software.

2.2 Hull Resistance modelling

The simulation considers the breakdown of the hydrodynamic resistance into its constituent components of skin friction, viscous pressure and wave pattern resistances (Molland et al, 2011), together with the aerodynamic resistance. A similar approach has been used previously for Olympic kayaks (Jackson, 1995), rowing shells

(Lazauskas, 1997) and outrigger canoes (Caplan, 2008). Caplan (2008), however, neglects the hydrodynamic interactions between the main hull and the outrigger. For the Va'a this interaction is considered to be potentially important, particularly since the outrigger (ama) position can be varied and there are no limits as to how close to the main hull it may be.

In the present study, therefore, empirical formulae are adopted for the first two components of resistance, whereas the wave pattern resistance is predicted using a linear potential flow method, commonly referred to as 'thin ship theory'. Thin ship theory has proved suitable for the estimation of multi-hull craft wave pattern resistance in previous studies (Couser et al, 1998), capturing the interaction effects between slender multi-hulls accurately. This theory models the wave patterns of both the main hull and the outrigger, together with their interaction and thus allows investigation of alternative outrigger locations and their effects on hull resistance.

The viscous resistance is estimated in the same manner as Jackson (1995) and following standard naval architecture practice (Molland et al, 2011) as a combination of skin friction resistance and viscous pressure resistance. That is,

$$C_V = \frac{1}{2}\rho S V^2 (1+k) C_F ,$$

where, S is the wetted surface area of the main hull, ρ is the water density (taken as 1000 kg/m^3), V is the vessel speed, C_F the skin friction coefficient and *(1+k)* the form factor for the hull. The skin friction coefficient may be estimated using the ITTC 1957 correlation line (see Molland et al, 2011),

$$C_F = \frac{0.075}{\left(\log(\mathrm{Re}) - 2\right)^2}$$

which in turn depends on the Reynold's number (Re), given as a function of the hull length (L), vessel velocity (V) and the kinematic viscosity of the water (υ) as,

$$\mathrm{Re} = \frac{VL}{\upsilon}.$$

In this case, in the absence of experimental measurements or alternative data, the form factor *(1+k)* is assumed to be the same as that of a rowing shell due to the similarities of hull form (long and slender with fine ends) and is taken from Scragg and Nelson (1993) as,

$$k = 0.0097\left(\theta_{entry} + \theta_{exit}\right)$$

where θ_{entry} and θ_{exit} are the half-angles of entry and exit of the waterplane, respectively. The same model is applied to estimate the viscous resistance of the main hull and outrigger (ama).

The aerodynamic resistance is modelled using the relationship described by Jackson (1995),

$$D_F = \frac{1}{2}\rho_a V^2 D_A$$

with ρ_a being the air density and D_A the drag area, the product of the frontal surface area of the boat and athlete and an appropriate drag coefficient. Jackson (1995) suggests that a drag area of 0.4m^2 is suitable for a K1 kayak and so for the main hull this is taken as a suitable value. For the ama, it was estimated this would have a tenth of the frontal area of the main hull and so the drag surface area was estimated at being around 0.04m^2. A suitable drag coefficient is suggested to be 1.0 (Jackson, 1995). One effect that has been neglected in the present calculations is the added resistance caused by any wind encountered.

2.3 Propulsion model

The boat is propelled from the interaction between the water and the paddle face, powered by the athlete. The paddle stroke is split into the recovery phase, where no work is done, and the power phase. The force exerted on the paddle is not evenly distributed throughout the power stroke, with maximum force occurring when the blade face is perpendicular to the water surface and minimum force occurring when the paddle enters and leaves the water.

Whilst it is becoming possible to investigate numerically the forces developed by a paddle blade as it enters the water and passes a hull using computational fluid dynamics (see, for example, Banks et al, 2013), such methods are presently too time-consuming for a race simulation. In this case the paddle velocity is modelled as a half sine wave for the 'power phase' of the stroke and a recovery phase during which no force acts on the blade. The 'power' and recovery phases are assumed to be of equal duration in the present model.

The paddle velocity is used to calculate the propulsive force, through combination with the boat velocity, the projected area of the paddle (A_P) and a suitable drag coefficient (C_D). The projected area was evaluated by measuring paddles currently in use. The drag coefficient used was 1.28, taken as that of a flat plate perpendicular to the flow from Hoerner (1965). The paddle force is thus obtained as,

$$F_D = \frac{1}{2}\rho C_D A_P \left(V_{boat} - V_{paddle}\right)^2 .$$

This is a very simplified way of representing the athlete and paddle within the simulation and is not without flaws. The velocity profile of an actual stroke is likely to be different as the blade face is kept vertical for as long as possible to maximise power output. In Va'a technique, the athlete also switches the side they paddle on several times during the race. None of these aspects of the stroke are included in the current model. The stroke rate will also vary throughout the race, being much lower at the start and rapidly increasing as the boat accelerates, until a more or less steady-state stroke rate is achieved. This could be included in the model with a stroke rate profile included.

3. Results and Discussion

In order to verify the accuracy of the simulation, values of race parameters were chosen to match a World Championship race from 2011. Since the exact model of paddle used is unknown, values were taken for a typical race paddle. All parameters are shown in table 2.

Table 2: Input values for simulation based on chosen race scenario.

Variable	Value
Race length (m)	200
Stroke rate (/min) (race average)	83
Athlete mass (kg)	75
Boat mass (kg)	13.8
Paddle length (m)	1.27
Paddle area (m^2)	0.065
Water temperature (^{i}C)	26.5
Ama x-position (m)	0.0
Ama y-position (m)	1.0

The simulation was conducted using a 4th order Runge-Kutta fixed time step solver, with a time step of 0.1s. Race times and speeds obtained are shown in table 3.

Table 3: Predicted and measured race time values.

Quantity investigated	Race data	Simulator data	% difference
Race time (mins:secs)	01:08.80	01:08.20	-0.87
Average speed (m/s)	2.91	2.93	0.72
Maximum speed (m/s)	3.80	3.22	-15.26

Whilst overall race time is predicted accurately, the maximum speed as predicted is lower than the maximum speed recorded in the race. This may be a result of assuming that stroke rate is constant throughout the race, or as a result of errors in the estimation of the resistance or propulsion components of the simulation. The boat velocity throughout the race is shown in figure 2. This indicates that the model behaves in a realistic manner. The boat accelerates until a steady state velocity is reached. This is achieved in around 17 strokes. The steady state velocity fluctuates with the recovery phase of the paddle stroke. From video footage of an actual race it appears as though a steady state velocity is reached in around 10 strokes. The achieved velocity is also higher than that predicted in the simulation, as seen in table 3. This suggests that the force exerted by the paddle should be higher, or the resistance components are over-estimated in the simulation.

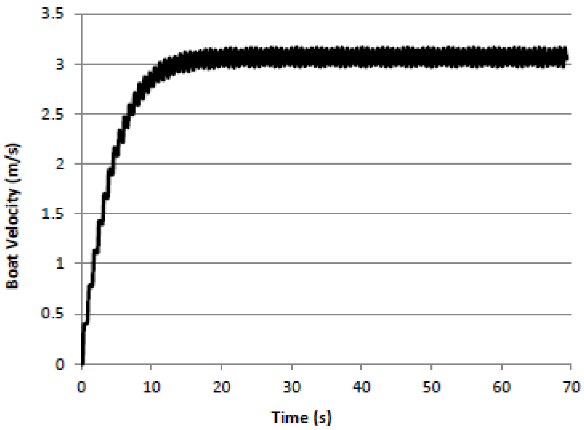


Figure 2: Predicted boat velocity against time for a 200m race.

The components of resistance are presented in table 4, for four different athlete masses. In each case the resistance values quoted are the maximum values experienced in a 200m race simulation. It can be seen that the aerodynamic resistance varies with athlete weight, since it is a function of the boat speed and this decreases slightly as athlete weight increases. The wave-making resistance increases due to the greater displacement of the boat with a heavier athlete. The increase in displacement causes a corresponding increase in wetted surface area and hence viscous resistance.

Table 4: Comparison of resistance components for different athlete masses.

Athlete mass (kg)	Steady-state velocity (m/s)	Viscous resistance (N)	% of total resistance	Aerodynamic resistance (N)	% of total resistance	Wave-making resistance (N)	% of total resistance
65	3.02	31.86	82.61	2.96	7.68	3.74	9.70
75	2.93	31.95	82.44	2.80	7.22	4.01	10.34
85	2.85	32.01	82.17	2.66	6.82	4.29	11.02
95	2.79	32.16	82.28	2.54	6.50	4.39	11.22

Jackson (1995) suggests that the wave-making and aerodynamic resistance for a four man kayak account for 12% and 6% of the total resistance, respectively. The predicted values in table 4 are in good agreement, since a four man kayak is similar in length and fineness to a Va'a, although travels faster. It is thought that the propulsion variables have the largest effect on predicted race time and the under-estimation of maximum speed seen in table 3 is most likely due to shortcomings in the propulsion model described in section 2.3. A change in the % of the total stroke time taken by the 'power' phase and the recovery phase (from the equal time adopted), could have a marked effect on boat velocity, as could the manner in which the force is delivered through the stroke. A further area for enhancement would be the inclusion of wind effects, acting at different strengths and from different directions, as this is known to cause considerable problems during a race, particularly with regards to directional stability.

4. Conclusions

A race-time simulation model for the Paralympic sprint canoe, the Va'a, is demonstrated to predict race-time accurately, but to under-predict the maximum velocity. This under-estimation of maximum velocity is thought to be due to the simplicity of the propulsion model adopted in the model. Investigations into improvements in the propulsion model should look at better replicating the actual athlete paddling technique in terms of time spent in the 'power' phase of the stroke, the paddle velocity and the hydrodynamic force generated by the paddle. The introduction of a variable stroke rate through the race would also be beneficial.

Notwithstanding these deficiencies in the propulsion model, the present model may be a useful tool for investigating the influence of hull design variables, such as the ama spacing and longitudinal position on predicted race-time performance. The method of predicting the wave resistance adopted in the model leads to it being particularly suited to such a task.

Acknowledgements

The authors wish to thank Team GB coach, Mr. John Court of Trentham Canoe Club for providing access to boats, paddles and information in support of this study. The practical support of Mr. John Griffiths is also gratefully acknowledged.

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