‘Development of a Vpp based rating for J-Class Yachts’

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Abstract

The J-Class was originally one of a number of level rating classes, developed under the ‘Universal Rule’, rating at 76 feet. The class was designated for each of the three America’s Cup series from 1930 to 1937. Most of the yachts were either scrapped or laid up at the end of the 1930’s, but more recently interest in the class has revived. Following refits and restorations, and one complete rebuild, there is now a class association and interest in further builds is strong, with two new boats already well into construction and fit out.

For several years, the J-Class Association has run regattas based upon a Time Correction Factor (TCF) calculated using the standard WinDesign Velocity Prediction Program (Vpp). In 2007, the Association transferred the operation of this rating system to the Wolfson Unit both as a measure of independence and further to refine the process.

The form and proportion of the J-Class contrast dramatically with those of the modern yachts which have largely driven developments in VPP hydrodynamic formulations in recent years. This paper describes the some new formulations geared specifically to the J-Class yacht, and generally applicable to the traditional yacht. The fact that the keel and hull of the traditional yacht cannot be rationally delineated is an issue and an approach to obviate this problem is described. Data from 1936 towing tank experiments of 1/24th and 1/8th-scale J-Class models are reanalyzed for new J-Class Vpp formulations. These include a specific wave resistance formulation and extensions to the heel drag model that treat vertical volume distribution and the relatively long overhangs of the J yacht.

The overall approach to rating J yachts is described, along with a summary description of the existing fleet. The final TCF ratings are presented and compared with previous years’ ratings, as well as the Time Allowance calculated under the ‘Universal Rule’ itself, and a comparison is made of these different ratings for the existing J-Class competitors in their modern configurations.

Introduction

The J-Class has its roots in the evolution of sailing yacht design on both sides of the Atlantic. Driven by different measurement systems in the late 19th century, the trend in Europe was narrow and deep, and in America, wide and shallow. Neither system produced particularly satisfactory results. Interestingly, the much criticized plank-on-edge designs of that period had lower ballast ratios that the America's Cup Class (ACC) yachts of today.

Both traditions were clearly in need of better regulation, both to improve design and also to make racing more equitable. Around the turn of the 20th century two new rating rules were introduced that have stood a reasonable test of time: the International Rule in Europe, still with us in the form of the metre yachts, 6, 8 and 12; and the Universal Rule in America, developed by Herreshoff and adopted in 1902 by the New York Yacht Club.

The rule itself was a simple formulation relating an effective rating in units of length, to the length, sail area and displacement of a yacht.

$$Rating = \frac{0.2 \times L \times \sqrt{S}}{\sqrt[3]{D}}$$

This rating could be used in two ways, either to provide handicapping data on a time allowance in seconds per mile, again worked out by Herreshoff, or as a means of grouping yachts by level rating, which is where the alphabetic I, J, K, L down to S classes arose. The I class yachts had a rating of 88 feet, J's of 76 feet, and so on to the S class with a rating of 17 feet. Like all rules, the 'Universal' gradually became hedged about with particular restrictions as designers worked out how to adapt designs to achieve a favourable rating, but its fame today rests on its role in the history of the America's Cup, and the legacy of the 'Big Boats' still sailing today.

In 1928, the rule was adopted for future America's Cup racing, and more specifically the J-Class rating length, but it was not until 1930 that the first of three Cups was raced under it, pitting Sir Thomas Lipton's last Shamrock V, against Enterprise. Two further sets of races were held in J's, in 1934 Endeavour against Rainbow, and 1937 Endeavour II against Ranger. It was this era that still quintessentially defines opulence in yachting, even now in a time where sailing super yachts of 60 – 70 metres in length have become almost unremarkable. That era did not last, and of the ten J-Class yachts built in the period, all except Shamrock were scrapped or laid up by the end of the 1940's.

But they were not forgotten, and as large yacht sailing prospered again in the late 20th century interest in the boats revived. Velsheda and Endeavour were rescued from their mud berths, and rebuilt. Shamrock was restored closer to her original rig, and when they reappeared on the classic racing circuit a new J-Class Association was formed to preserve the tradition and promote the class. The success of the association means that new boats have been, and are being, built to the class rules, the most important of which is that a yacht can only call itself a J if it is built to lines of those either built or proposed in the 1930's.

Where the original boats were seen only as day racers, the restored and newly built vessels are true super yachts. They have interiors, and engines, and tanks of fuel and water. All of this means that none complies with the original J rating under the Universal rule, so, if they were to compete equitably, a new method of rating needed to be determined.

Initial use of the existing WinDesign Vpp for J-Class rating

Providing a rating for a modern J-class is not so simple. They can be measured under IRC, and indeed often race under that rule, but like all modern rules it is more suited to a modern design where keels and rudders are separate from the hulls. So when the Dijkstra office was asked to propose a method of handicap that could be used for J-Class only regattas, they turned to the modern Velocity Prediction Program, that can match aerodynamic and hydrodynamic performance with inherent stability, and predict times around courses. Dijkstra & Partners were already using the WinDesign Vpp in their project work, so it was natural for them to select it for working on the J ratings as well. As consultants to all of the existing vessels and prime movers in the formation of the J-Class association, they were particularly well endowed with data on the yachts.

As with the modern rating formulations, the existing Vpp contains information more akin to the modern yacht forms than long keel J boats. So it was necessary to try and break the yacht up into a hull and separate keel. Methods to do this were devised, and, using a particular version of the program in order to maintain stability of the resulting speed predictions, TCF values were calculated by comparing the predicted times around windward-leeward and random courses against a base boat, Velsheda in her 2001 configuration was chosen as the base boat.

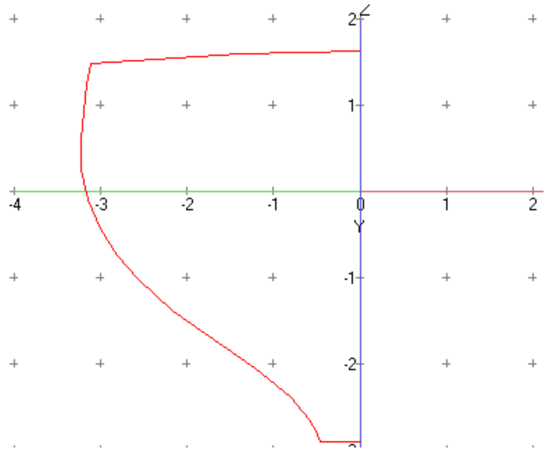
The resulting TCF values were used successfully for several seasons, as the data matched the perceived performance on the race course sufficiently well, particularly as racing was restricted to the three existing boats, and more often to Endeavour and Velsheda alone.

As interest grew, and with the advent of a new boat with the 2004 rebuild of Ranger, it became clear that the existing Vpp-based system had its limitations. Alongside this, the interest of other designers in J-Class projects meant that Dijkstra and Partners needed to stand back from direct control of the ratings. At this point, the J-Class Association asked the Wolfson Unit to undertake the required calculation in order to provide rating certificates, and also to examine the methods used and suggest improvements.

The first phase of work undertook to examine the sensitivity of the Vpp formulations to various hull parameters typical of a J-Class yacht, and in particular to the nature of the separation of the natural hull form into a canoe body hull and separate keel.

Although previously a more complex separation had been used to achieve this, it had already been proposed to base separation upon the concept of a horizontal cut at the level of the inflection of the midship section as shown in Figure 1. A new keel was then added below the horizontal cut, with the required volume and wetted area such that, when combined with the hull, it matched the full hull.

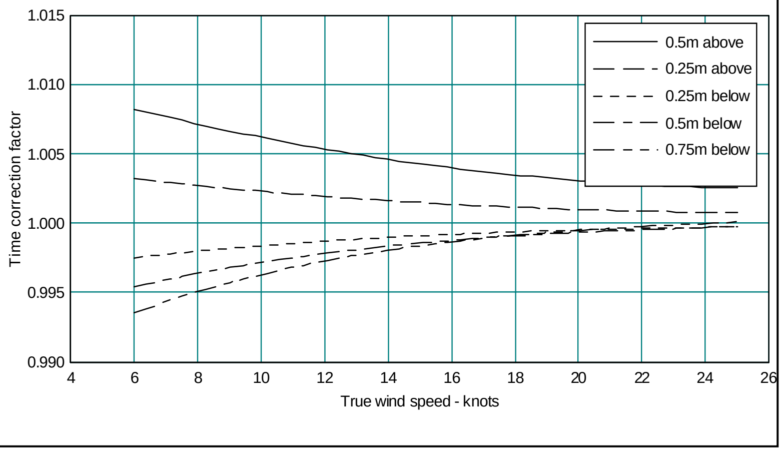
Figure 1. Example of keel cut location on J-Class



A study was undertaken by progressively moving the horizontal cut above and below the inflection point and calculating TCF values for each variant hull, as compared with the original cut position.

The resulting data are shown in Figures 2 and 3, and immediately highlight a significant problem with the use of this forced separation method within the Vpp. Different hull forms, even within the restricted range of J-Class shapes, reacted differently to the height of cut.

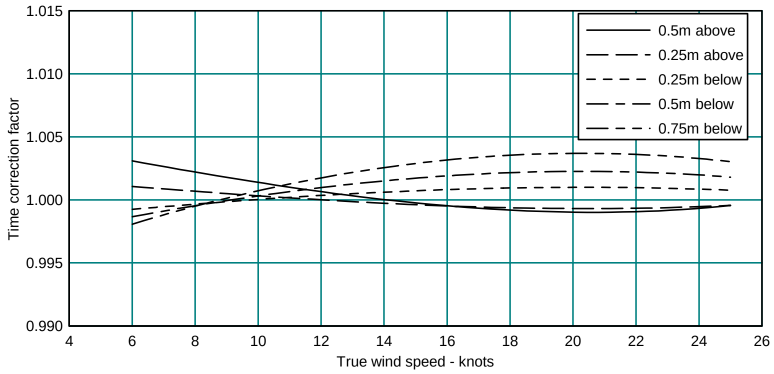
Figure 2. Velsheda, variation in TCF with top of keel position



For Velsheda, there is a relatively simple variation in the TCF both with increasing wind speed and also as the horizontal cutting plane moves up and down.

However, for Ranger, in Figure 3, the situation is significantly different. Not only do the TCF data vary in a more complex manner with wind speed, but also there is a different relationship with the height of the cutting plane that separates hull and keel.

Figure 3. Ranger, variation in TCF with top of keel position



These differences imply sensitivity to cutting height that differs between yachts, and therefore means that the final ratings would depend upon the choice of position of the top of the keel. Clearly this is not an acceptable option, and so on this basis, the concept of separation into hull and keel was discarded.

However, the Vpp's hydrodynamic force calculations are based on upon such a separation, and so new methods had to be found in order to characterize the performance of classic long keel yachts in general, and J-Class in particular.

Existing Vpp methods

The modern yacht is characterized by a canoe body with clearly-defined appendages. This separation of parts has made the calculation of hydrodynamic forces relatively straightforward, inasmuch as we use one set of methods for the canoe body and then another set for the appendages.

For example, the canoe body viscous drag calculation typically uses ITTC frictional formulation, the Reynolds number based on *full* wetted length. A form factor derived by various means is applied to the frictional drag. By contrast, the appendage viscous drag estimate for fins and rudders works with 2D airfoil sections and associated data or methods. Bulb drag calculations assume streamline symmetric bodies with associated data and methods. For the calculation of upright wave drag, the effect of the appendages on the canoe body wave making drag is implicit in the canoe body wave drag formulations. The difference in upright wave drag due to the appendage variations between wide varieties of modern racing yachts is included assuming a standard modern yacht hull-keel configuration.

Traditional yachts with long integrated keels and attached rudders such as the J-Class do not easily divide into canoe body and appendage. In essence there is just the yacht, and the rudder, keel and hull are all melded into one elegant form. Nevertheless, various approaches have been used to try to apply to the classic yacht the "modern" canoe body/appendage procedures of LPP and VPP.
One approach is to place a horizontal cut at some water plane, as described above, with the consequences shown, others rely on direct use of the hull parameters in order to determine resistance in the normal characterization as a combination of elements due to upright, heeled and induced parts, but little data had previously been used to check these.

Original towing tank data

Background

Happy with the performance of his new J-Class Endeavour II, T.O.M Sopwith in August 1936 issued an America's Cup challenge. Set for the end of July 1937 rather than the traditional month of September, he hoped there may be more wind in Newport at that time of year. In America the feeling was that no existing American J-Class was up to the task of defending against the Endeavour II. Harold Vanderbilt asked Starling Burgess and Olin Stephens (Sparkman & Stephens) to start on new designs.

The designers embarked on a model testing program at Stevens Institute of Technology (SIT) in New Jersey. A new 100-ft tank had been installed in 1935 and an era of testing very small yacht models had begun, largely due to methods and efforts by Professor Kenneth S.M. Davidson, instructor of mathematics and Director of the tank, as described in the first reference [1]. The original tank test reports were kindly made available by Sparkman & Stevens for this project.

Each designer drew two new models designated 77A through 77D. A wider model 77F was tested, as well as some rudder and counter modifications to 77D and 77C, respectively. Models of several existing yachts were to be tested as well, including competitors in the 1934 Cup: Endeavour and Rainbow. A model of 1930 J-Class Weetamoe, previously tested [SIT Rept. 12] was included in the analysis. Table 1 lists the model particulars. Model 77C would become the basis for the yacht Ranger.

The new models followed the direction from Vanderbilt for the new design to go to the maximum of 87' waterline, longer than earlier J-Class yachts. There had been concerns about longer waterlines and heavier displacement in light airs, but these had been allayed after Vanderbilt had tried ballasting down Rainbow to 87' and found her light air performance to be surprisingly good.

Table 1. Full Scale Particulars of 1:24 Scale Models tested at SIT – 1936

		Particulars			***Wetted Surfaces***			***Remarks***
Name	**SIT** *#*	**Lwl** *m*	**Bwl** *m*	**Dspl** *kg*	**No board** *m2*	**Board** *m2*	**Total w/b** *m2*	
Weetamoe #3	97	25.756		153460	194.17	---	194.170	*Previously tested - SIT R12*
Endeavour I	120	25.604	6.490	148844	196.12	7.804	203.927	*with estimated centreboard*
Rainbow	130	25.604	6.276	150064	191.57	6.736	198.306	*with 1936 keel*
77A	134	26.518	6.608	166028	206.71	8.919	215.633	*new 87' design*
77B	133	26.518	6.416	167189	205.79	8.919	214.704	*new 87' design*
77C	131	26.518	6.279	169163	203.46	8.919	212.382	*new 87' design(**Ranger)***
77D	132	26.518	6.206	167479	201.79	8.919	210.709	*new 87' design*
77C2	131	26.518	6.279	169163	213.22	8.919	222.137	*77C rud profile ext. Not Tested*
77D2	132	26.518	6.206	167479	211.82	8.919	220.743	*77D rud profile extended*
77E	138	26.518	6.279	167682	203.65	8.919	212.567	*77C counter lower, f'body mod*
77F	139	26.518		167334	205.32	8.919	214.240	*new wide model*
77CE	140	26.518	6.279	169163	203.46	8.919	212.382	*lower aft profile of 77C*

A wide range of tests and analyses were conducted, including upright, heel-yaw, sea keeping and balance. SIT Report 34 presents the results of a "J-Boat Investigation for H.S. Vanderbilt, Esq. relating to the design of Ranger" [2]. The model scale was 1:24.

The typical size for tank models up to this point was at least 10 feet. A larger model of Ranger (77C) was tested at 1/8-scale at the Experimental Model Basin at the Navy Yard in Washington, D.C on November 4, 1936. At that time there may have been some concern about inadequate turbulence stimulation on the small models. In April 1937 a supplemental report [3] describes an investigation into the accuracy of the sand strip corrections, comparing to the drag of bare model behind a separately towed strut. The original comparison between Ranger and Endeavour was reworked and the report concluded with the statement, "Differences between the two boats are, of course, smaller than in Report 34, but an advantage for Ranger is still indicated."

Basis for new formulations

In the development of new formulations for the J-Class, we wanted to use as much of these data as possible. This effort required various approaches to "back-out" useful information from SIT Report 34. Of the tested models we only have hydrostatic information for Ranger (77C) and Endeavour I. Note that the J-Class yachts now race in heavier conditions than these. The particulars used for the test data analysis for Ranger and Endeavour are shown in Table 2.

Table 2. VPP Particulars, Endeavour I and Ranger (77C) corresponding to SIT 1/24 Tank Tests

	Endeavour	Ranger 77C
Dspl	148500	169162
Dsplc	148500	169162
Lwl	25.606	26.657
Lsunk	31.883	34.334
Bwl	6.49	6.275
Bmax	6.748	6.411
Tc	4.648	4.583
Tmax	4.648	4.583
Ax	11.573	12.693
Cp	0.496	0.488
Awp	116.17	118.15
LCB	-3.02	-2.91
LCF	-3.03	-3.02
GYR	0.25	0.25
PIPA	0.083	0.083
VCB	-0.928	-1.387
ProjA	67.389	73.402

Wetted Surface

Heel	End	77C
0	192.593	202.111
2	192.587	202.097
10	192.211	202.139
25	191.356	203.380
40	197.961	209.569

LWL

Heel	End	77C
0	25.606	26.657
2	25.598	26.651
10	25.419	26.497
25	25.275	26.424
40	25.930	27.301

The main task was to come up with the wave making drag for 77C. Knowing that the SIT procedure used the Schoenherr frictional formulation based on a 70% waterline Reynolds number, the so-called run-in procedure with a Prohaska plot yields a viscous correction factor that includes an aggregate sand strip drag and any bona-fide form factor. Thus the viscous drag and sand strip drag is subtracted from the SIT total full scale drag to give an estimate for wave resistance. This method actually allowed for very consistent curves of wave resistance when plotted against Froude number, irrespective of the original sand coefficients.

Using these data, a new base wave resistance curve was developed for the J-Class formulations. The parameters in the WinDesign wave resistance formulations include length-displacement ratio, beam-to-draft ratio, prismatic coefficient and longitudinal centre of buoyancy. Some small adjustments were made to other coefficients in the VPP, but at this point there is insufficient data from two tests carried out at 1:24 scale to suggest making any significant changes, other than to recast the base curve to fit these upright data. There is an indication from the 1:8 scale tests conducted at EMB that the small models had dropped out of turbulent flow at the lower speeds (Fn < 0.275).

Revised Vpp formulations

Formulations for the calculation of wave drag, heel drag, induced drag and viscous drag all include the Bwl/Tc ratio. Bwl is clear enough, but for a long keeled yacht the canoe body draft Tc is not. The approach we use here defines a substitute non-dimensional $\frac{B}{Tc'}$ ratio as:

$$\frac{B}{Tc'} = \frac{Bwl^2}{0.9\,Amax}$$

Modifications of various formulations for new J-Class data use this substitute B/T to achieve fits to various data. One can back out a substitute canoe body draft:

$$Tc' = \frac{0.9\ Amax}{Bwl}$$

In the following sections we discuss how the Vpp computes various hydrodynamic forces. The principal focus is on those areas where the formulations have been modified or extended for the J-Class. More details on the formulations contained in the Vpp can be found in various papers and reports listed in the references [4] through [8].

Wave drag

Wave resistance is a function of the following four parameters:

Vol/Lwl^3	*Displacement-length ratio - total volume over length cubed.*
Bwl/Tc	*For J-Class, this becomes the effective B/Tc'*
LCB	*longitudinal location of centre of buoyancy*
Cp	*canoe body prismatic coefficient ∀/(Lwl Ax) where Ax is maximum canoe body sectional area.*

These parameters are based on the physical characteristics of the boat in a given condition of flotation. An upright wave resistance C_w is evaluated as the sum of a Fn-dependent base coefficient and products of the above parameters with Fn dependent coefficients A_0 - A_6.

$$C_w = A_0 + A_1\ \forall/Lwl3 + A_2\ Bwl/T' + A_3\ LCB + A_4 LCB^2 + A_5\ Cp + A_6\ Cp^2$$

These coefficients were developed over the years for various types of boats and do not follow IMS or DELFT formulations. For the J-Class the base coefficient has been set to match the wave resistance curve from the 1:24 scale tank tests of Ranger. Thus model 77C from tank tests reported in SIT Report 34 is used as the base boat for the revised wave resistance formulations. The displacement-length ratio coefficients have been modified to be more applicable to these heavier traditional boats.

Heel drag

For the upright yacht with no side forces, wave drag and viscous drag comprise our estimate of total drag. We generally assume the hydrodynamic interaction between these two components is small enough to ignore. As it heels the yacht presents an asymmetric immersed form and generates side force, sinkage and trim typically vary as well. These heel-related changes and the asymmetric distribution of hydrodynamic pressure on the hull and its appendages produce a different wave system, creates induced drag, and affects the viscous drag.

The category of heel drag is in fact the collection of these various interrelated heel effects. For convenience, some of these effects are reasonably included in other categories:

- The variation in canoe body wetted surface with heel is accounted for in the canoe body drag calculations, and thus shows up as part of hull viscous drag.
- The effects of heel on induced drag are accounted for in the induced drag calculations.

The remaining effects relate mostly to wave drag changes and include:

- Change in effective length as the boat heels and trims.
- Asymmetry of hull as measured by upright *Bwl/Tc* ratio. Whilst the hull's wave system is modified by the asymmetric immersed shape, generally it is the appendages that produce

additional wave systems which are typically deleterious. The waves related to the appendages coming closer to the surface often make up the majority of the heel drag.

- Asymmetry due to a "flare" as parameterized by the ratio of *Bmax/Bwl*

In addition to wave drag changes, heel-related form drag is added. Whilst the change in the boundary layer thickness and wake as the boat heels is not easily evaluated – with modern, beamier boats a pattern has often emerged in which increasing *Bwl/Tc* results in an increase in form factor. Certain yachts with full after bodies and high aft prismatic coefficients, e.g. International Metre Class will have high form factor upright, but this varies little with heel. So the basic heel model in the VPP will have a small component of form drag change as a function of *Bwl/Tc*, but not to *Cp*.

These components are shown in Table 3 below. The development of successful heel drag formulations requires a mixture of theory, experimentation and common sense. Because we have access to the LPP data for Ranger and Endeavour at this point, we have worked with their rather limited 1:24 scale heeled-and-yawed data. Determining the relative importance of various components requires some juggling with the limited data.

Table 3. Various components of heel drag formulations, noting the J-Class extensions.

Nom.	**Physical**	**Description**	**Function Parameters**	
			Std WinDesign	**J-Class Model**
R_{h1}	Wave	Change in effective length at sailing flotation	*Le (φ)*	*Le (φ)*
R_{h2}	Wave	Effect of overhangs with heel	not included	Lsunk – overhang effect
R_{h3}	Wave	Asymmetry of Hull	*B/T*	*B/T*
R_{h4}	Wave	Appendages volume & lift depth change heel	not included	VCB
R_{h5}	Wave	Additional mid-hull asymmetry due to flare	Bmax/ Bwl	Bmax/Bwl – less important
R_{h6}	Viscous	Form drag change	*B/T*	*B/T* – less important

For the J-Class yachts under consideration, there is not a wide range of *B/T* ratio. There would be little "flare drag" and in cases where there is tumblehome one might say there is a negative flare effect – and it would be very small component. Also there will be negligible effect of the change of form factor with heel between the various yachts presently under consideration. Thus many of the functions that exist in the standard monohull Vpp formulations will have little effect on relative J-Class performance.

However, there are two areas for which extensions to the standard formulations are developed. The first area treats the fact that the J-Class has very long overhangs compared with the modern yacht. The overhangs on modern yachts have less of an influence on the change of effective length with heel than might be the case with the J-Class. Consequently a modification is included that will add a fraction of the "sunken length" to the heeled length *Le(φ)* as a function of heel. The second extension is due to the fact that the long keels of the J-Class effectively spread out the concentrated keel and rudder wave that are significant constituents of the modern yacht heeled wave pattern. Both these extensions to the standard WinDesign formulations are described below.

Inclusion of long overhang in heel drag

As the boat heels over the effective waterline length changes and this is evaluated by the LPP for five heel angles. In the VPP the heeled length is used to evaluate the heeled Froude number, which is then used as the argument in the wave resistance formulation. In the VPP we actually evaluate the difference in the wave drag with this modified *Fn* compared to wave drag with upright *Fn*. This gets thrown in as heel drag and can be negative or positive:

$$R_{h1} = R_w\left(Fn_{upr}\right) - R_w\left(Fn_\theta\right)$$

As the J-Class yacht heels, the effect of the overhangs as measured in the LPP as the sunken length L_{sunk} comes into play. Additionally it should be pointed out that L_{sunk} does enter the picture at low speeds, but as the bow and stern wave effectively extend the length of the boat L_{sunk} becomes influential. Because we presently calculate L_{sunk} only for the upright condition, we will apply a function to introduce a portion of the additional length as the boat begins to heel. R_{h2} is the component of heel drag we have introduced for the J-Class, but for convenience we calculate the sum $R_{h1} + R_{h2}$ by using the revised heeled-overhang length L_{h2} for the Fn_θ in the above equation. This heel-overhang length is:

$$L_{h2} = (1 - t)L(\emptyset) + t\, k_{h2}\, L_{sunk} f(\emptyset)$$

where

$$k_{h2} \sim 0.25$$

$$f(\emptyset) = \frac{sin^{2.5}\emptyset}{sin^{2.5}25}$$

$$t = sin^4[\pi(Fn - 0.025)] \ \ldots Fn < 0.525$$

$$t = 1 \ \ldots Fn > 0.525$$

Effect of vertical centre of buoyancy on heel drag

In the standard Vpp wave resistance model, a component of heel drag is tied to B/T ratio. For the modern yacht a higher B/T will generally result in higher heel drag, partly due to adverse affect on the yacht's wave system from greater asymmetry, and more so from the keel wave. A linear function of B/T ratio has seemed work reasonably well in the past.

$$R_{h3} = k_{h3}\,\frac{B}{Tc'}R_w$$

where

$$k_{h3} \sim 0.015$$

For the J-Class, the coefficient k_{h3} in the above equation is less than what is used in the standard monohull formulation because of the lack of the concentrated keel wave. For the long keel yachts, more of the total volume is placed further down in the long keel. Thus for the J-Class yacht it seems more appropriate to consider how wave making drag is modified as the yacht heels due to vertical movement of volume towards the free surface. The characteristic parameter to which we will tie this movement will be the vertical center of buoyancy *vcb* of the yacht. Our approximation will broadly derive from hydrodynamic theory from J-Class era, part of which is presented in 1936 by Havelock [9].

The approximation is derived from the fact that the Kelvin wave spectra can be written as an integral over a Havelock distribution defining the hull surface. We assume this distribution is not a strong function of depth and also where the primary wavelength $(2\pi\, v^2/ g)$ is large compared to the maximum draft.

Wave resistance is proportional to the integrated square of the magnitude of the spectra function, and in that function we approximate the depth dependence as $(T_c\, e^{k\, z}b)^2$ where $k = g/v^2$ and z_b is the vertical centre of buoyancy $(z_b < 0)$. We will remove the T_c from the relationship because it is not an explicitly defined parameter for the J-Class, and it's effect is treated through the *B/T* ratio term used in drag component R_{h3}.

We can write the following approximation for one component of heel-related wave resistance:

$$R_{h4} = k_{h4}\, r^2 \;\; R_W$$

where

$$r = \frac{e^{k\, z_b} - e^{k \cos\phi\, z_b}}{e^{k\, z_{b0}} - e^{k \cos\phi\, z_{b0}}}$$

$$k_{h4} \sim 0.05$$

$$z_{b0} = reference\ vertical\ center\ of\ buoyancy = -0.9284$$

$$R_w = upright\ wave\ drag$$

Imagine a hypothetical J-Class, call it Yacht 1 (Y1), that has a vertical volume distribution yielding a deeper vcb than Yacht 2 (Y2). As a yacht heels, its relative movement of *vcb* from its upright position is *vcb (1-cos φ).* As both yachts heel, the Y1 *vcb* moves a greater distance toward the free surface than Y2 *vcb*. The result will be an increase in this component of wave drag for Y1 relative toY2. The effect of this relative shift depends on the speed, through the wave number. It should be emphasised this is but one factor of upright wave drag, and the wave drag would be different for Y1 and Y2 -- the J-Class with a lower *vcb* would probably have smaller *Bwl*, as in the case of Ranger vs. Endeavour.

Viscous Drag

The usual approach in WinDesign for the calculation of canoe body viscous drag uses the ITTC frictional formulation line with a canoe body form factor. A typical form factor for a modern yacht is about 1.10 ± 0.02. Big bustles featured in International Twelve-Metre class, for example, may be in excess of 1.14.

$R_{vc} = q\, k_{form}\, C_f\, S_c(\phi)$

In which:

k_{form}	*canoe body form factor, typically ranging from 0.10 - 0.15 (use .125 as a typical value)*
Cf	*0.075/(log(Rn)-2)² friction coefficient from the ITTC formulation and Reynolds number Rn is evaluated using full wetted length.*
$Sc(\phi)$	*canoe body wetted surface at heel ϕ in still water*

On top of the canoe body drag is added the appendage drag. There are various methods for this in WinDesign which generally use 2D airfoil section drag coefficients as a function of Reynolds Number, or alternately ITTC formulation with widely-used form factor fits as presented by Hoerner.

Because of sensitivity of results to the cut line approach previously used shown, the normal method needs to be modified. Other methods were considered such as slicing up the whole yacht into longitudinal strips and then applying some blend of 2D airfoil sections and ITTC frictional formulation, but this just introduced one more layer of arbitrariness.

Like many others, we have carried out numerous approaches over many years of tank testing and research to calculate hydrodynamic viscous drag. As a gesture to traditional methods with a traditional yacht, we employ the procedure of calculating a single effective Reynolds Number for the whole yacht. The reference length for the *Rn* is 70% of waterline length (in racing flotation.) The form factor is set to 1.00 and there are no separate appendage calculations. The total wetted surface calculated is calculated as a function of heel angle.

Induced Drag

The induced drag is calculated using the convenient concept of effective span Te according to:

$$Di = L^2/(2\pi q\, Te^2),$$

The effective span Te is calculated by

$$Te = k_1\, f(Vol/L^3)\, f(Fn)\, f(B/T)\, f(\phi)\, Tr$$

The reduced draft *Tr* is evaluated according to slender body theory assuming a semicircular cross section and trailing edge of keel near the position of maximum sectional area:

$$T_r^2 = T_{max}^2 - 2A_x/\pi$$

Comparison with the original test tank data

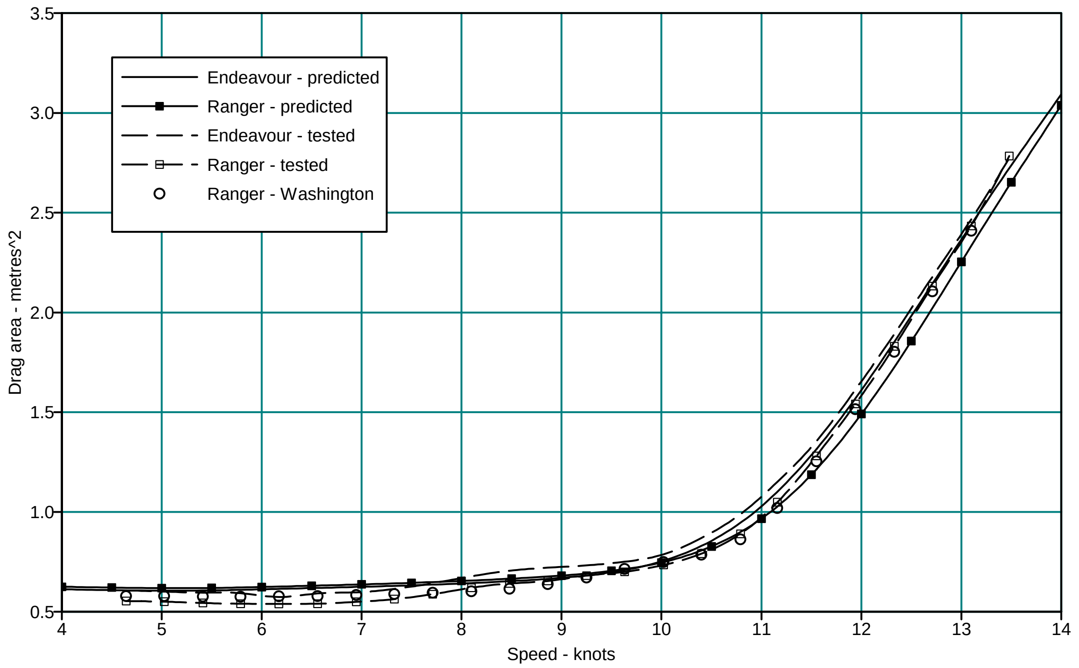
Using the new formulations in the Vpp allows a comparison of the predicted resistance data with those determined in the original test programme for both Endeavour and Ranger.

The upright resistance comparisons are shown in Figure 4 in terms of Drag Area, where:

$$D.a = \frac{R}{0.5\rho V^2}$$

Data are presented for both vessels, as predicted by the Vpp and as tested at Stevens, with the larger scale tests on Ranger, at Washington, included.

Figure 4. Upright Drag comparisons



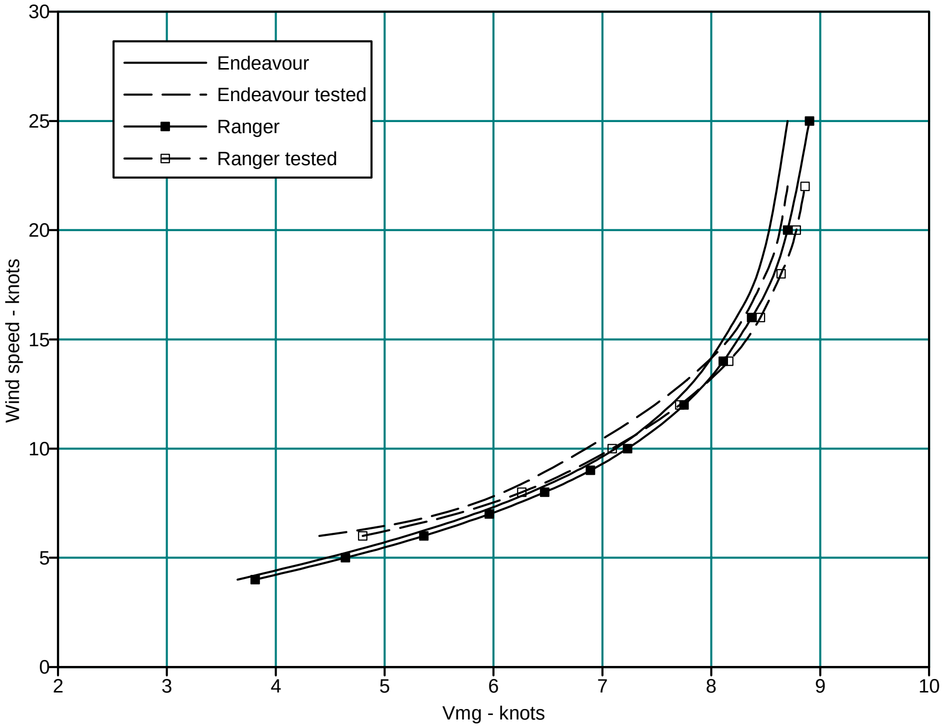
The data predicted from model testing shows that Ranger has less resistance over the speed range from 5 to 13.5 knots, with a reasonably consistent difference at speeds less than 12 knots. The Washington data are similar to the Stevens Institute values, although with less evidence of a hump between 6 and 10 knots, and an indication that the resistance is slightly lower at speeds above 11 knots.

The differences between the two Vpp predictions are smaller than those found in the tank at speeds up to 11 knots, with little indication of a hump. The data indicate that Ranger may fare a little better under the Vpp rule than she should in lighter winds. At speeds above 11 knots the Vpp predictions differ a little more than the tank results, but with Ranger always predicted to have less resistance than Endeavour.

Figure 5 presents the predictions of velocity made good to windward from both the tank and Vpp, as all of the heeled tank work was done with a centerboard, this has been replicated in the comparison, although the modern J’s do not use them.

There is broad agreement between the predictions and tank results, both in absolute and relative terms although the Vpp predicts better performance for both boats at wind speeds less than 8 knots than the tank analysis.

Figure 5. Windward comparisons



Final formulation

The final version of the Vpp formulations allow J-Class vessels to be entered into the Vpp in the normal way, by specifying their hydrostatic and stability qualities within the associated Lines Processing Program (Lpp), and adding specific rig and sail wardrobe data. This latter point is of note, as the lack of an extensive wardrobe can be accounted for in the final rating and should not prove to be a disadvantage.

The J-Class Association rules call for ratings in terms of Time Correction Factors. These are calculated in three wind bands to cover light medium and heavy air racing.

The TCF values are calculated by using the Vpp’s inbuilt Race Committee function with its standard Windward-Leeward, and Circular Random courses. By comparing the performance of the yacht in question against the standard Velsheda 2001 data file, TCF are calculated at a number of specific wind speeds by dividing the time for Velsheda 2001 by the time achieved for the test yacht. The Light wind TCF is the average value between 6 and 9 knots wind speed, the Medium wind TCF the average of 9 and 14 knots, and the Heavy wind TCF the average of 14 and 20 knots.

Finally, in order to maintain close racing, a maximum rating is calculated, and existing or new yachts cannot exceed this if they are to be eligible to race.

Comparison with the original Universal Rule

Although the success of the Vpp rating method can only be measured in its acceptance on the race course, it is instructive to compare its recommended time corrections with those of the original Universal Rule.

The three J Class boats currently racing have moved away from their level rating of 76 feet, as shown in Table 4. Under the original time allowance tables determined by Herreshoff, vessels of different rating receive or give a single time on distance on the races course.

Table 4. Current rating under the Universal Rule

	Universal rating		Time allowance
	metres	feet	seconds
Velsheda	23.9	78.31	0
Endeavour	23.7	77.66	1.02
Ranger	24.9	81.54	-4.87

Running the Vpp on the boats' current configurations leads to predictions of time around one mile courses, either pure windward-leeward or in all directions denoted as a circular random course. These times can be compared, and corrected both by use of the original time allowance, and also the TCF values calculated in each wind band. The results are shown in Table 5, and show significant differences between the boats. The Universal Rule deltas shown in the table are constructed by subtracting the course time for Velsheda from that of Endeavour and Ranger, and then subtracting the Time Allowance of Table 4. The Vpp deltas are arrived at by application of the rated TCF, calculated itself by the Vpp in each wind band, to the course time of Endeavour or Ranger, and subtracting Velsheda's time.

For racing between Ranger and Velsheda, both systems produce close racing as indicated by the small predicted time differences (deltas) under either method. However, the situation when racing Endeavour against Velsheda is different. In light and medium winds Endeavour is at a significant disadvantage if racing under the Universal rating, this is partially due to her lack of an asymmetric sail, but, even if one is added to her wardrobe the Vpp based rating provides much closer results.

Table 5 Comparison of Vpp and Universal Rule results

Course Times and deltas in seconds for one nautical mile

TWS	Velsheda		Endeavour					
knots	WL	CR	WL	CR	Universal deltas		Vpp deltas	
6	710	522	734	539	23.0	16.0	2.8	1.8
7	627	466	645	479	17.0	12.0	-0.6	-0.5
8	568	429	581	438	12.0	8.0	-3.8	-3.3
9	525	402	534	409	8.0	6.0	-6.4	-4.5
10	491	383	499	388	7.0	4.0	1.5	0.0
12	447	357	452	361	4.0	3.0	-0.9	-0.7
14	419	340	423	343	3.0	2.0	-1.5	-1.4
16	400	329	403	331	2.0	1.0	0.7	-0.3
20	375	313	376	315	0.0	1.0	-1.1	-0.2
25	357	301	359	303	1.0	1.0	0.0	-0.1

Ranger					
WL	CR	Universal deltas		Vpp deltas	
706	518	0.9	0.9	0.5	1.1
623	462	0.9	0.9	0.0	0.6
563	424	-0.1	-0.1	-1.4	-0.8
520	397	-0.1	-0.1	-1.7	-1.1
487	377	0.9	-1.1	1.9	0.7
442	350	-0.1	-2.1	0.3	-0.8
413	333	-1.1	-2.1	-1.0	-1.1
393	321	-2.1	-3.1	1.1	0.1
366	305	-4.1	-3.1	-1.4	-0.3
348	292	-4.1	-4.1	-1.8	-1.6

Endeavour - assymetric					
WL	CR	Universal deltas		Vpp deltas	
726	533	15.0	10.0	0.3	0.1
639	474	11.0	7.0	-1.9	-1.7
577	435	8.0	5.0	-3.5	-2.9
532	408	6.0	5.0	-4.5	-2.4
499	388	7.0	4.0	2.4	1.2
452	360	4.0	2.0	0.0	-0.5
423	343	3.0	2.0	-0.7	-0.4
403	331	2.0	1.0	0.7	0.2
376	314	0.0	0.0	-1.1	-0.7
359	302	1.0	0.0	0.0	-0.7

Conclusions

The Vpp model of J-Class yachts appears to perform well in comparing the upwind performance, both in terms of absolute and relative performance between Endeavour and Ranger, when compared with the results from the tank testing.

There is slightly greater divergence of data when comparing the upright resistance between the Vpp model and the tank tests on the basis of Drag Area, which might tend to favour Ranger’s rating in light winds, and penalise her in heavy winds, but these differences are small, and, well within the expected uncertainty of any prediction method based solely upon hull parameters, such as a Vpp.

The method currently proposed within the J-Class Vpp version, is as good as can reasonably be expected from such a tool. Although alternative Vpp models could be created, the variation in performance prediction between the different boats may be altered, but is not likely to be improved.

Should the J-Class Association wish better to predict the true potential performance differences between the existing and future fleet, a set of model tests could be undertaken, under its auspices, that would provide detailed hydrodynamic performance data for each design, and thus overcome the inevitable assumptions that underlie a parameter based prediction.

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