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Full-scale trials in varying depths of water on a King Class fast patrol vessel

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SYNOPSIS

This paper describes full-scale trials carried out on a Royal Hong Kong Police 'King Class' 26 m semi-planning fast patrol boat at various depth/draft ratios, between 2.96 and deep water over a range of Froude numbers between 0.3 and 0.8. Results are also given in one location for the effect on performance of varying displacement and for both inward- and outward-turning propellers. Reference is made to previous comprehensive trials carried out at the turn of the century on the HDMS Makrelen, Söbjörnen, S.119 and HMS Cossack.

A summary of powers, speeds, dynamic trim and shaft rev./min is given, together with the resulting analysis for wake and resistance.

The results show significant variations in wake and the interdependence of depth of water, resistance, displacement, propeller type and rotation on the performance of this type of vessel particularly when traversing the hump speed. This same interdependence of variables is shown to be independent of, but affected by, the wave of translation as it comes in phase with maximum dynamic trim and wake at lower depth/draft ratios.

The depth at which shallow water effects can be expected is shown to increase with Froude number and a formula is given for this. The actual speed of translation varies with the depth/draft ratio. The single unique point at which that speed equals $\sqrt{gH}$ appears to have significance with respect to maximum power requirements to traverse the hump. Wake is found to increase with displacement. Maximum wake at constant displacement is found to occur at about a depth/draft ratio of 6 over the whole speed range. The peak wake however at all locations and conditions occurs during passage of the hump in the Froude number range of 0.4 to 0.45. Two phenomena are proposed to explain the observations and results, i.e. 'Finite bottom effect' and 'Surfing'. The worst trial conditions are shown to occur at Froude numbers between 0.5 and 0.6 combined with depth/draft ratios of 3.5 to 6.0. The power for traversing the hump peaks at a depth/draft ratio of approx. 5.0, and thereafter, reduces, although pre-hump power requirements are shown to continue to increase as the depth/draft ratio decreases at the corresponding Froude number.

Data are presented to enable preliminary powering calculations based on published information and that given in this paper. A new full-size propulsive coefficient is proposed which combines roughness factor, power prediction factor, relative rotative and hull efficiencies. This coefficient is then further incorporated in a modified Froude resistance coefficient derived from an analysis of these trial results and comparisons are made with data published by others. This allows the designer to make a power prediction in varying depths of water using the data in this paper for resistance and wake with open water charts only, the remaining components for overall propulsive efficiency being incorporated in the modified Froude resistance coefficient. Finally, comments are made on the present model tank and theoretical procedures for power predictions of this type of craft.

INTRODUCTION

Although data must exist in the archives of various navies and specialist shipbuilders one must, more often than not, refer back to the classic HDMS *Makrelen*, *Söbörjen*, S.119 and HMS *Cossack* trials[1, 2, 25] of nearly a century ago to find any worthwhile full-size date on the performance of high-speed craft in varying depths of water. Full-scale data on wake and other propulsion coefficients in any comprehensive manner are also virtually nonexistent, although work by Canham[3], Bailey[4] and Marwood & Silverleaf[21] have touched on this aspect.

The 3 days continuous trials which this paper represents and 2 days on a previous sister ship perfecting trials procedures, requires a tolerant set of shareholders and a building programme that is not delayed. Displacement, sea bottom profile and length of 'mile' will vary from location to location and trial run to trial run. Whilst we were extremely fortunate with the weather throughout, model test conditions cannot exactly be repeated.

The author served a 5 year shipbuilding apprenticeship as well as studying at Poplar Technical and Regent Street Polytechnics in London. He then spent time at sea as a Marine Engineer with Port-line and had 3 years with Vickers Shipmodel Experimental Tank where his interest in resistance, propulsion and full-scale experimentation began. He joined Kort Propulsion Ltd. in 1963, where his knowledge of powering and manoeuvring of ships was further developed under T.E. Hannan, eventually rising to executive director. Subsequently he specialized in management both with companies in Europe and the Far East, where, for the last 10 years, he was General Manager of the Chung Wah Shipbuilding & Engineering Co. Ltd. shipbuilding division. He is now Managing Director of Richard Dunston (Hessle) Ltd. Despite the author's management specialization he has not lost interest in the subject of 'resistance and propulsion' and the present paper is a reflection of that continued interest.

NOMENCLATURE

Symbol		Units
A_m	Immersed midship section area	m^2
A_s	Propeller blade area ratio (BAR)	
B	Beam static water line	m
B/d_m	Beam/mean draft ratio	
β	Average deadrise angle over planing area	degrees
©$_{app}$	Froud's resistance constant from model data including appendages $= \dfrac{P_E \times 579.7}{\Delta^{2/3} \times V_S^3}$	
©$_z$	Modified Froud's resistance constant from trial data $\dfrac{579.7 \times P_S \times \eta_o \times \eta_s}{V_S^3 \times \Delta^{2/3}} = ©_{app} \times \dfrac{1+x}{\eta_p}$	
D	Propeller diameter	m
d_a	Draft at aft perpendicular	m
d_m	Mean draft	m
d_f	Draft at fwd perpendicular	m
F_n	Froude number (based on length) $\dfrac{v}{\sqrt{gL}} = 0.1643 \dfrac{V_S}{\sqrt{L}}$	
F_{nH}	Froude number (based on depth) $= \dfrac{v}{\sqrt{gH}}$	
H	Water depth	m
I	Static depth of immersion propeller axis at centre propeller boss	
J	Advance coefficient $\dfrac{v_e}{nD}$	
K_Q	Propeller torque coefficient $\dfrac{Q}{\rho n^2 D^5}$	
K_T	Propeller thrust coefficient $\dfrac{T}{\rho n^2 D^4}$	
L	Length static water line	m
L/B	Length/beam ratio	
L/H	Length/depth ratio	
LBP	Length between perpendiculars	m
LCG	Longitidinal centre of gravity aft amidships	%

$$\frac{0.5\,\text{LBP} - \text{CG}_{\text{from aft perp}}}{L} \times 100\%$$

Symbol		Units
Ⓜ	Froude's length constant $\dfrac{L}{\nabla^{1/3}}$	
n	Shaft revolutions per second (rev./s)	s^{-1}
N	Shaft revolutions per minute (rev./min)	min^{-1}
P	Propeller pitch	m
P/D	Propeller pitch ratio	
P_E	Effective horse power including appendages (EHP)	kW
P_S	Shaft power	kW
Q	Shaft torque	Nm
T	Shaft thrust	N
V_A	Speed of advance	knots
v_c	Theoretical critical wave speed $\sqrt{gH}$	ms^{-1}
V_c	Actual critical wave speed	knots
v_e	Speed of advance	ms^{-1}
v	Ship speed	ms^{-1}
V_s	Ship speed	knots
w_t	Taylor's wake fraction (Torque identity) $\dfrac{V_S - V_A}{V_S}$	
η_o	Propeller open water efficiency	
η_h	Hull efficiency	
η_r	Propeller relative rotative efficiency	
η_s	Shaft transmission efficiency	
η_p	Propulsive efficiency $\eta_h \times \eta_r$	
η_z	Fullsize propulsive coefficient = $\dfrac{1+x}{\eta_p}$	
OPC	Overall propulsive coefficient $\dfrac{\eta_z}{\eta_o}$	
$(1+x)$	Power prediction factor	
∇	Displaced volume	m^3
Δ	Displacement	tonne
τ	Dynamic trim angle	degrees
ρ	Water density (1025 S.W.)	kg m^{-3}
g	Gravitational acceleration (9.81)	ms^{-2}

Apart from where new symbols have been introduced the nomenclature is as defined in ref 22.

The purpose of this paper is to put before the profession a set of raw data of tests carried out on a hard chine high-speed patrol craft in varying depths of water. Hopefully, the data, analysis and comment will give a more solid reference for the performance of high-speed craft. As the raw full-scale test results are given as completely as possible any interpretation or form of analysis other than that which appears in this paper may be easily made.

At present there appears to be an 'overkill' of data on resistance based solely on model tests. Much of this is not reliable enough on its own especially when a builder has to put his name to a contract having a stiff speed penalty. As will be shown, other major components are involved which can affect overall performance in addition to resistance, particularly around the hump speed. Some rethinking may be needed with respect to the presentation and measurement of propulsion factors particularly by model test establishments with relatively narrow tanks.

The tests described were carried out at one location on one of the 'King Class' fast patrol boats built for service with the Royal Hong Kong Marine Police. Measurements of the principal parameters shaft torque, rev./min and ship speed, were taken on trials in five different depths of water, also at three different displacements and with both inward- and outward-turning propellers at one location.

VESSEL PARTICULARS

The craft is of the hard chine type, as shown in the midship section (Fig. 1) and general views of the hull (Fig. 2), fitted with full shaft bossings and inboard offset spade rudders behind twin fixed-pitch propellers. The vessel's relevant hull and propeller particulars are as shown in Table 1.

Fixed-pitch propellers having flat face aerofoil-type sections, similar to Troost 'B' series [5] but thickened at the trailing and leading edges to inhibit debris damage, were fitted for these trials. The computed open water data for the mean pitch of 1.086 is shown in Fig. 3. For comparative purposes data have been added from ref. 5 (extrapolation as given by NSMB) and ref. 6 over the trial's analysis range. The mean pitch ratio of port and starboard propellers was used throughout the analysis.

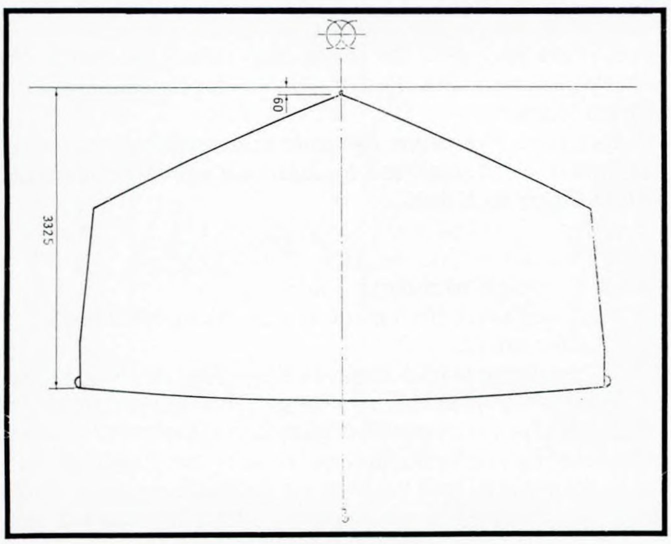

Fig. 1. Midship section

Trial locations

The trial sites, which were all within Hong Kong waters, are as shown in Table 2, the mean bottom profiles being shown in Fig. 4. Distances between markers and buoys other than locations with official 'mile' posts were taken by radar targeting, using the vessel's own RM 1226C radar fitted with a digital range marker indicator accurate to 0.01 of a nautical mile and cross-checked on sea charts. Throughout, only the bottom formed a boundary to the test site and the width of sea may be considered to be infinite.

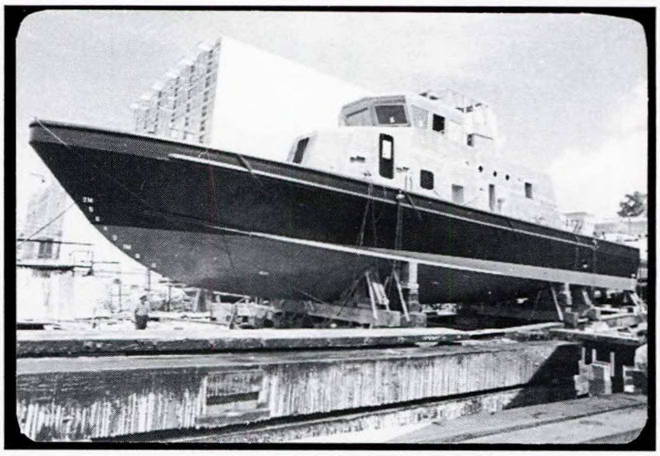

Fig. 2 (*a*). General view of underwater hull

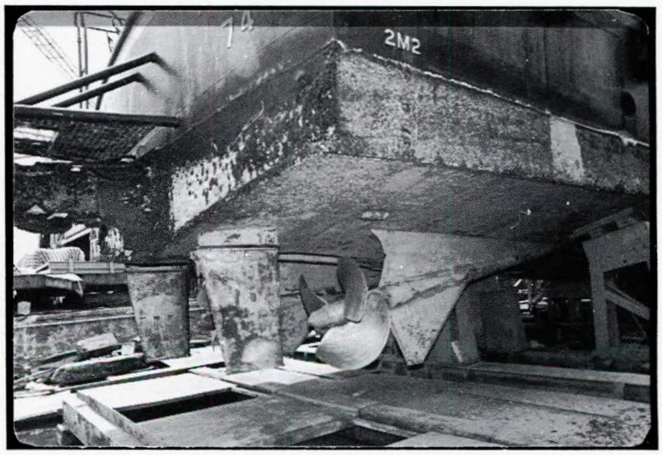

Fig. 2 (*b*). General view of underwater appendages

Measurement methods

Speed. Speeds were measured by stopwatch against fixed markers, i.e. overground speed. The mean of one each-way run at each nominal speed was used for presentation in the results. Readings at approximately 30 s intervals (1 min intervals at Cheung Chau) were also taken from an EMY 1/C speed log gauge during each trial run. This effectively measures speed through the water or relative change of speed through water when it differs from the original calibration.

The speed log was calibrated as closely as possible against mean speeds over ground on the Junk Bay mile at the nominal trial displacement of 97.0 tonnes.

Shaft revolutions. Shaft revolutions were measured by a digital infra-red counter fitted adjacent to each shaft, remotely measured and digitally displayed. Readings were taken at

Table 1. Hull and propeller particulars

Hull (at 97 tonnes)	
Length static wl. (*L*)	24.60 m
Beam static at wl. (*B*)	5.60 m
Static position of LCG aft amidships	7.5 %
Midship area at 1.59 m draft (A_m)	5.12 m^2
Average deadrise over planing area (β)	19 degrees
Propeller	
Propeller diameter (*D*)	1.00 m
Propeller pitch ratio port (*P/D*)	1.0855
	1.086 mean
Propeller pitch ratio starboard (*P/D*)	1.0864
BAR	1.08
Material	Copper/nickel/ aluminium alloy

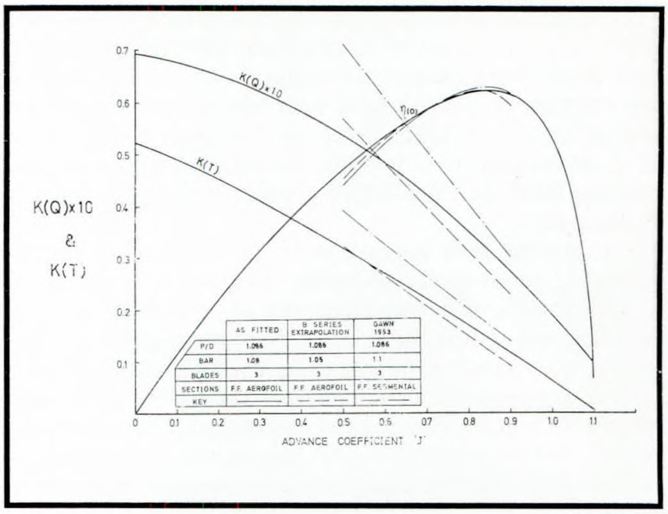

Fig. 3. K_T/K_Q chart

Table 2. Trial sites particulars

Table no.	Site	Length (nautical miles)	Average depth (*H*) (m)	Markers	Headings (degrees)	Depth/draft ratio (H/d_m)
11	Junk bay (1)	1.00	10.52	Mile posts	329/149	6.41
6	Junk bay (2)	1.00	10.17	Mile posts	329/149	6.40
10	Junk bay (3)	1.00	9.91	Mile posts	329/149	6.52
9	Junk bay (5)	1.00	9.80	Mile posts	329/149	6.16
3	Silvermine bay	1.69	7.12	Fixed beacons	260/80	4.48
4	Silvermine bay (adjusted)	1.69	4.70	(See discussion of results)	260/80	2.96
5	Adamasta	1.20	6.56	Buoys	226/46	4.13
7	Cheung Chau	3.00	16.45	Mile posts	245/65	10.35
8	East Lamma Channel	1.22	34.01	Fixed beacons	305/125	21.39

approximately 40/60 s intervals depending on the 'time' over the mile. For analytical purposes the mean rev./min of port and starboard shafts were used. Additional spot check readings were taken by a hand held SPM TAC-10 remote tachometer, taken directly from the gearbox outlet coupling at each run and checked against the digital readings.

A third waterjet propulsor was also fitted to this craft which was allowed to trail freely during these trials, the resulting induced rev./min values were measured on the jet drive shaft.

Shaft torque. Shaft torque was measured by a specialist company independent of the shipyard using a strain gauge bridge bonded-on each shaft and transmitted by an FM system fitted to each one. The output signal was proportional to the shaft torque and remotely measured and digitally displayed. Readings were taken at approximately 40/60 s intervals depending on the time over the 'mile'. Independent of the torsion meter, the engine fuel rack settings, which give a relative indication of torque, were taken during each trial run. The mean shaft power port and starboard computed from shaft torque and rev./min was used for analysis.

Displacement. Displacement was measured by reading draft marks at the commencement and completion of trials at each location. Estimation of displacement at each individual run was by use of data obtained from fuel consumption and cross-checked against the above displacement readings. No other liquids were consumed or added during the course of trials at each location.

Dynamic trim angle. Dynamic trim was measured during each run on a level table using a calibrated spirit level and fixed height sliders such that

$$\tau = \cos^{-1}\left(\frac{S}{X}\right)$$

where S = height of slider;
X = distance from pivot to slider along spirit level calibration;
τ = dynamic trim angle.

Fuel consumption. Fuel consumption was measured by FRO gear-type rotor positive displacement flow meters fitted to the engine fuel pump suction and return lines. Readings were taken at the end of each trial run. An approximate check of fuel usage was obtained by taking readings from Mobrey fuel tank meters fitted on the bridge at the end of each trial run. These

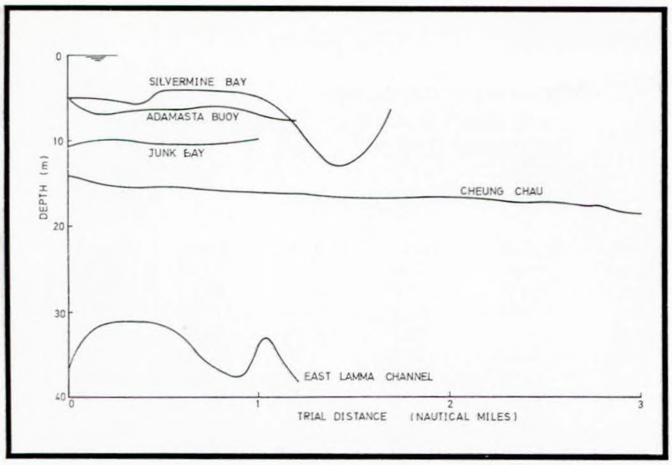

Fig. 4. Mean bottom profiles

figures were then cross-checked by taking fuel tank soundings at commencement and completion of trials at each location.

Water depth. Depth readings were taken from an ED 162 echosounder on a pen recorder and at 30 s intervals (1 min intervals at Cheung Chau) during each run from a digital display concurrent with the speed log readings.

Trial conditions

Apart from the displacement variation trials in Junk Bay each location trial commenced as close to 97 t and 0.65° static trim as practical. In spite of variation in passage times to trial locations repeatability was reasonably good. All trials at each location commenced at the lowest rev./min and completed with maximum rev./min. The exception to this was on the deep water East Lamma Channel location trials where maximum rev./min were commenced first to enable the maximum speed runs to be completed before dark. Two runs indicated in the East Lamma Channel have suspect speed readings due to an undetected fault developing in the gyro repeater which may have affected course keeping. One double run was performed at each rev./min at each location.

At the start of each double run the procedure was to set the rev./min as closely as possible to the corresponding main engine rev./min as follows, and take whatever shaft speed and power resulted (900, 1100, 1300, 1540, 1600, 1650, 1720, 1800 and maximum rev./min).

The straight run up to the mile varied depending on location environment. Generally this was 0.5 to 1 min where no restriction applied. The Junk Bay mile south end requires a gentle curve into the mile with an approximately 10 s (depending on speed) straight section to the mile. Observation of the speed log indicated that this did not seriously affect the speed measured on the mile if the rudder angle on the curve was kept to a minimum.

Presentation of results

Basic data. Tables 3 to 11 inclusive show as-measured and analysed results for the trials on the above craft. The analysed results for $©_z$ include a correction for a third propulsor jet unit which was allowed to idle, declutched, during the trials. The amount of correction was deduced from trials on the Junk Bay mile of a sister vessel not fitted with a jet, the comparison of which is shown in Fig. 5. The correction for displacement was made using the data from Tables 6, 10 and 11. It was further assumed that the power required to overcome the jet configuration power augment was the same at all locations and displacements at corresponding F_n values.

Tables 3 to 9 inclusive show values for a common start displacement of approximately 97.0 t at the various measured distances listed in Table 2. Table 9 however is for a trial carried out on the Junk Bay mile but with outward-turning propellers. Power, dynamic trim angle and wake fraction are shown graphically for varying H/d_m ratios against F_n in Fig. 6 and a comparison of inward- and outward-turning propellers in Fig. 8, with corresponding shaft rev./min also added.

Tables 10 and 11 show trial results and analysis for start displacements of approximately 90 and 102 t respectively on the Junk Bay mile. Power, dynamic trim angle and wake fraction are shown against F_n at varying displacements in Fig. 7.

In each of the Tables lines 1 to 7 are as-measured data and lines 8 to 16 are analysed. All other parameters have been analysed using as-measured mean shaft power, rev./min, pitch ratio and speed.

Resistance. Fig. 9 shows a cross-plotting of data taken from refs. 8 and 9 in the deep water mode. Toros data has been adjusted to allow for appendages using the method proposed by Bailey[7]. However, the w_t values over the relevant deep-water speed range taken from Fig. 6 of this paper were used for appendages forward of the propeller and ship speed with no wake correction throughout for those aft of the propeller. The latter thus makes some allowance for propeller race speed.

Calculations in this manner lead to an almost constant $\delta ©_{app}$ for appendages having an average value of 0.072 over the F_n range considered in this paper. The variation either side of this

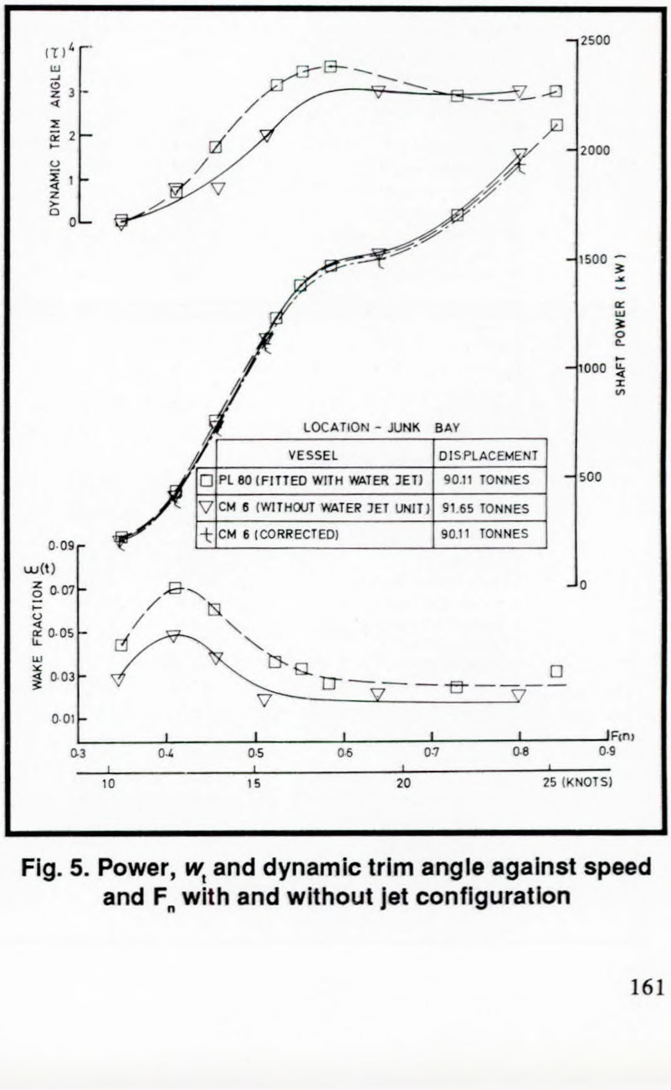

Fig. 5. Power, w_t and dynamic trim angle against speed and F_n with and without jet configuration

Table 3.

Location:	Silvermine Bay	Mean water depth (H):	7.12
Course (odd runs):	260	Static mean draft (d_m):	1.59
Course (even runs):	80	Depth/draft (H/d_m):	4.48
Start displ.:	97.16	LCG:	7.51 % aft
Static w.l. length (m):	24.59	Static trim angle (degrees):	0.68

As-recorded data									
0 Run no.	1 & 2	3 & 4	5 & 6	7 & 8	9 & 10	11 & 12	13 & 14	15 & 16	17 & 18
1 Ship speed (knots)	10.12	11.92	12.89	13.93	16.40	17.96	19.61	21.13	23.92
2 Mean shaft (rev./min)	444.8	541.6	640.6	755.2	795.9	818.4	856.7	893.1	967.2
3 Total mean power (kW)	231.0	450.0	787.0	1348.0	1450.5	1491.5	1639.0	1776.5	2139.0
4 Displacement	97.16	97.12	97.05	96.95	96.83	96.7	96.58	96.45	96.33
5 Rack setting	9	9.2	10.65	13	13.2	13.5	13.85	14	15.5
6 Dynamic trim (degrees)	0.08	0.56	1.65	3.40	3.75	3.06	2.81	2.84	2.73
7 Mean speed log (knots)	9.87	11.85	12.65	13.55	15.40	17.18	18.81	20.44	23.03
Analysed data									
8 K_Q x 10	0.436	0.470	0.497	0.520	0.478	0.452	0.433	0.414	0.392
9 Open water eff. (η_o)	0.577	0.548	0.521	0.496	0.542	0.564	0.577	0.585	0.603
10 Advance coeff. (J)	0.679	0.623	0.576	0.535	0.611	0.654	0.682	0.711	0.745
11 Wake fraction (w_t x 10)	0.331	0.829	0.725	0.602	0.393	0.344	0.347	0.263	0.240
12 Froude no. (F_n)	0.335	0.395	0.427	0.461	0.543	0.595	0.649	0.700	0.792
13 © overall	3.492	3.955	5.203	6.727	4.851	3.956	3.419	3.006	2.574
14 *d* ©$_z$ (due to w.j.)	0.201	0.167	0.216	0.202	0.102	0.062	0.039	0.026	0.020
15 ©$_z$ (corrected for w.j.)	3.291	3.788	4.987	6.525	4.749	3.893	3.380	2.980	2.553

Table 4.

Location:	Silvermine Bay (adjusted)	Mean water depth (H):	4.7
Course (odd runs):	260	Static mean draft (d_m):	1.59
Course (even runs):	80	Depth/draft (H/d_m):	2.96
Start displ.:	97.16	LCG:	7.51 % aft
Static w.l. length (m):	24.59	Static trim angle (degrees):	0.68

As-recorded data									
0 Run no.	1 & 2	3 & 4	5 & 6	7 & 8	9 & 10	11 & 12	13 & 14	15 & 16	17 & 18
1 Ship speed (knots)	10.10	11.83	12.65	13.39	16.00	18.44	20.16	21.53	24.21
2 Mean shaft (rev./min)	444.7	541.4	639.8	754.4	795.1	820.2	858.1	894.4	969.5
3 Total mean power (kW)	231.2	448.4	797.2	1359.9	1458.4	1461.7	1604.4	1752.5	2142.1
4 Displacement	97.16	97.12	97.05	96.95	96.83	96.7	96.58	96.45	96.33
5 Rack setting	9	9.2	10.65	13	13.2	13.5	13.85	14	15.5
6 Dynamic trim (degrees)	0.08	0.56	1.65	3.40	3.75	3.06	2.81	2.84	2.73
7 Mean speed log (knots)	9.85	11.76	12.41	13.02	15.02	17.64	19.34	20.83	23.31
Analysed data									
8 K_Q x 10	0.436	0.469	0.505	0.526	0.482	0.440	0.422	0.407	0.390
9 Open water eff. (h_o)	0.577	0.548	0.512	0.486	0.536	0.573	0.585	0.594	0.604
10 Advance coeff. (J)	0.679	0.624	0.562	0.522	0.603	0.672	0.700	0.723	0.748
11 Wake fraction(w_t x 10)	0.314	0.747	0.790	0.471	0.291	0.316	0.346	0.269	0.295
12 Froude no. (F_n)	0.334	0.392	0.419	0.443	0.530	0.611	0.668	0.713	0.802
13 © overall	3.516	4.031	5.479	7.486	5.194	3.639	3.123	2.846	2.490
14 *d* ©$_z$ (due to w.j.)	0.201	0.165	0.181	0.213	0.116	0.054	0.033	0.025	0.021
15 ©$_z$(corrected for w.j.)	3.315	3.866	5.299	7.273	5.078	3.585	3.090	2.822	2.469

Table 5.

Location:	Adamasta Buoys	Mean water depth (H):	6.56
Course (odd runs):	46	Static mean draft (d_m):	1.59
Course (even runs):	226	Depth/draft (H/d_m):	4.13
Start displ.:	97.2	LCG:	7.28 % aft
Static w.l. length (m):	24.61	Static trim angle (degrees):	0.61

As-recorded data									
0 Run no.	1 & 2	3 & 4	5 & 6	7 & 8	9 & 10	11 & 12	13 & 14	15 & 16	17 & 18
1 Ship speed (knots)	10.29	12.04	13.18	14.52	14.95	15.70	19.69	21.22	23.94
2 Mean shaft (rev./min)	446.3	545.8	641.5	759.0	788.0	811.8	856.8	887.3	965.8
3 Total mean power (kW)	233.5	451.5	778.5	1337.0	1485.5	1604.0	1644.5	1753.5	2124.5
4 Displacement	97.2	97.17	97.13	97.03	96.91	96.8	96.69	96.63	96.54
5 Rack setting	8.5	9	10.5	13	13.5	14	14.2	14.75	15.8
6 Dynamic trim (degrees)	0.13	0.61	1.54	3.25	3.58	3.91	3.25	2.95	2.91
7 Mean speed log (knots)	10.01	11.87	12.81	13.91	14.29	14.85	18.30	19.93	22.97
Analysed data									
8 K_Q x 10	0.436	0.461	0.490	0.508	0.504	0.498	0.434	0.417	0.392
9 Open water eff. (η_o)	0.577	0.506	0.530	0.509	0.514	0.520	0.577	0.588	0.603
10 Advance coeff. (J)	0.680	0.638	0.590	0.558	0.563	0.575	0.681	0.708	0.746
11 Wake fraction(w_t x 10)	0.444	0.629	0.696	0.549	0.385	0.367	0.399	0.408	0.249
12 Froude no. (F_n)	0.341	0.399	0.436	0.481	0.495	0.520	0.652	0.703	0.793
13 © overall	3.357	3.554	4.895	6.042	6.216	5.867	3.386	2.941	2.546
14 *d* ©$_z$(due to w.j.)	0.194	0.157	0.231	0.179	0.158	0.125	0.037	0.026	0.020
15 ©$_z$ (corrected for w.j.)	3.163	3.397	4.663	5.864	6.058	5.742	3.349	2.915	2.526

Table 6.

Location:	Junk Bay (2)	Mean water depth (H):	10.17
Course (odd runs):	329	Static mean draft (d_m):	1.59
Course (even runs):	149	Depth/draft (H/d_m):	6.40
Start displ.:	97.12	LCG:	7.51 % aft
Static w.l. length (m):	24.59	Static trim angle (degrees):	0.68

As-recorded data									
0 Run no.	1 & 2	3 & 4	5 & 6	7 & 8	9 & 10	11 & 12	13 & 14	15 & 16	ADD. RUN
1 Ship speed (knots)	10.41	12.27	13.72	15.29	15.97	16.53	21.36	23.69	19.31
2 Mean shaft (rev./min)	448.5	536.3	643.3	760.3	792.3	810.3	898.0	962.0	852.8
3 Total mean (kW)	236.0	423.00	769.0	1296.0	1464.5	1547.0	1831.0	2126.5	1650.0
4 Displacement	97.12	97.1	97.06	97	96.91	96.81	96.71	96.61	96.76
5 Rack setting	9	9	10.45	13	13.4	13.7	14.65	15.15	——
6 Dynamic trim (degrees)	0.07	0.47	1.34	2.83	3.33	3.50	3.06	3.00	——
7 Mean speed log (knots)	10.04	11.94	13.21	14.81	15.31	15.97	20.44	22.96	19.71
Analysed data									
8 K_Q x 10	0.434	0.455	0.480	0.490	0.489	0.483	0.420	0.397	0.442
9 Open water eff. (η_o)	0.577	0.562	0.541	0.531	0.532	0.537	0.587	0.601	0.572
10 Advance coeff. (J)	0.682	0.648	0.608	0.591	0.593	0.603	0.704	0.739	0.669
11 Wake fraction (w_t x 10)	0.480	0.823	0.763	0.478	0.468	0.423	0.411	0.277	0.427
12 Froude no. (F_n)	0.345	0.406	0.454	0.506	0.529	0.547	0.707	0.784	0.639
13 © overall	3.279	3.496	4.377	5.234	5.203	5.007	3.004	2.620	3.569
14 d ©$_z$ (due to w.j.)	0.192	0.178	0.229	0.147	0.117	0.097	0.025	0.020	0.041
15 ©$_z$ (corrected for w.j.)	3.087	3.318	4.148	5.087	5.087	4.909	2.979	2.600	3.528

Table 7.

Location:	Cheung Chau	Mean water depth (H):	16.45
Course (odd runs):	245	Static mean draft (d_m):	1.59
Course (even runs):	65	Depth/draft (H/d_m):	10.35
Start displ.:	97.2	LCG:	7.42 % aft
Static w.l. length (m):	24.6	Static trim angle (degrees):	0.65

As-recorded data									
0 Run no.	1 & 2	3 & 4	5 & 6	7 & 8	9 & 10	11 & 12	13 & 14	15 & 16	17 & 18
1 Ship speed (knots)	10.19	12.07	13.67	15.91	16.80	17.41	18.69	20.22	22.86
2 Mean shaft (rev./min)	443.3	539.3	641.8	758.3	792.0	813.3	850.8	892.3	955.3
3 Total mean power (kW)	228.0	430.5	760.5	1245.5	1388.0	1495.0	1657.5	1847.0	2140.0
4 Displacement	97.2	97.14	97.06	96.93	96.77	96.61	96.45	96.26	96.07
5 Rack setting	8.8	9	10.5	12.4	13	13.5	13.9	14.8	16
6 Dynamic trim (degrees)	0.00	0.31	1.42	2.55	2.77	2.95	2.98	3.19	3.16
7 Mean speed log (knots)	9.67	11.57	13.04	15.02	15.85	16.50	17.76	19.12	21.97
Analysed data									
8 K_Q x 10	0.435	0.456	0.478	0.474	0.464	0.461	0.447	0.432	0.408
9 Open water eff. (η_o)	0.571	0.562	0.542	0.545	0.554	0.557	0.568	0.578	0.595
10 Advance coeff. (J)	0.681	0.648	0.612	0.617	0.634	0.638	0.661	0.685	0.723
11 Wake fraction (w_t x 10)	0.401	0.619	0.690	0.472	0.316	0.343	0.251	0.206	0.211
12 Froude no. (F_n)	0.337	0.400	0.453	0.527	0.556	0.576	0.619	0.670	0.757
13 © overall	3.340	3.737	4.385	4.584	4.416	4.301	3.935	3.529	2.916
14 d ©$_z$ (due to w.j.)	0.195	0.174	0.231	0.122	0.092	0.075	0.050	0.032	0.021
15 ©$_z$ (corrected for w.j.)	3.145	3.563	4.154	4.462	4.324	4.226	3.885	3.496	2.895

Table 8.

Location:	East Lamma Channel	Mean water depth (H):	34.01
Course (odd runs):	125	Static mean draft (d_m):	1.59
Course (even runs):	305	Depth/draft (H/d_m):	21.39
Start displ.:	96.95	LCG:	7.49 % aft
Static w.l. length (m):	24.59	Static trim angle (degrees):	0.67

As-recorded data									
0 Run no.	With w.j.	3 & 4	5 & 6	7 & 8	9 & 10	11 & 12	13 & 14	15 & 16	17 & 18
1 Ship speed (knots)	25.04	22.65	20.14	18.88	17.44	17.09	16.00	13.62	10.13
2 Mean shaft (rev./min)	984.8	957.3	889.3	846.3	819.5	797.0	758.5	645.3	444.0
3 Total mean power (kW)	2143.5	2142.0	1810.0	1621.5	1502.5	1404.0	1230.0	768.5	231.5
4 Displacement	96.95	96.84	96.76	96.67	96.57	96.48	96.4	96.32	96.28
5 Rack setting	15.8	15.9	14.5	14	13.1	12.8	12.5	11	8.35
6 Dynamic trim (degrees)	3.10	3.04	3.15	2.95	2.97	2.75	2.37	1.23	-0.05
7 Mean speed log (knots)	23.86	21.80	19.20	17.59	16.85	16.23	14.94	12.94	9.44
Analysed data									
8 K_Q x 10	0.373	0.405	0.427	0.444	0.453	0.460	0.468	0.475	0.439
9 Open water eff. (η_o)	0.610	0.596	0.582	0.570	0.563	0.557	0.550	0.544	0.574
10 Advance coeff. (J)	0.773	0.726	0.692	0.665	0.651	0.640	0.627	0.616	0.674
11 Wake fraction (w_t x 10)	0.150	0.058	0.100	0.342	0.089	0.330	0.369	0.544	0.428
12 Froude no. (F_n)	0.829	0.750	0.667	0.625	0.577	0.566	0.530	0.451	0.335
13 © overall	2.265	2.990	3.511	3.742	4.348	4.274	4.508	4.519	3.492
14 d ©$_z$ (due to w.j.)	——	0.021	0.033	0.047	0.075	0.083	0.120	0.235	0.201
15 ©$_z$ (corrected for w.j.)	——	2.969	3.478	3.695	4.273	4.192	4.388	4.284	3.292

Table 9.

Location	Junk Bay (5)	Mean water depth (*H*):	9.8
Course (odd runs):	329	Static mean draft (d_m):	1.59
Course (even runs):	149	Depth/draft (H/d_m):	6.16
Start displ.:	97	LCG:	7.52 % aft
Static w.l. length (m)	24.59	Static trim angle (degrees):	0.68

As-recorded data									
0 Run no.	1 & 2	3 &4	5 & 6	7 & 8	9 & 10	11 & 12	13 & 14	15 & 16	17 & 18
1 Ship speed (knots)	10.10	12.16	13.54	14.91	15.54	16.01	17.96	20.51	23.95
2 Mean shaft (rev./min)	445.0	542.5	641.8	757.8	789.0	807.5	850.8	894.5	981.3
3 Total mean power (kW)	222.5	427.0	747.5	1267.5	1402.5	1499.5	1682.5	1782.0	2171.5
4 Displacement	97	96.97	96.93	96.88	96.81	96.74	96.64	96.54	96.41
5 Rack setting	—	—	—	—	—	—	—	—	—
6 Dynamic trim (degrees)	0.16	0.35	1.18	2.60	2.93	3.33	3.41	3.03	2.73
7 Mean speed log (knots)	10.71	12.45	13.62	15.19	15.75	16.29	18.01	20.49	24.17
Analysed data									
8 K_Q x 10	0.419	0.444	0.469	0.484	0.474	0.473	0.454	0.413	0.382
9 Open water eff. (h_o)	0.587	0.570	0.548	0.536	0.544	0.546	0.562	0.591	0.607
10 Advance coeff. (*J*)	0.704	0.666	0.624	0.601	0.616	0.620	0.650	0.713	0.760
11 Wake fraction (w_t x 10)	-0.050	0.373	0.417	0.103	–0.133	–0.132	0.023	–0.078	–0.089
12 Froude no. (F_n)	0.334	0.403	0.448	0.494	0.515	0.530	0.595	0.679	0.793
13 © overall	3.446	3.681	4.488	5.577	5.534	5.433	4.448	3.331	2.619
14 *d* ©$_z$ (due to w.j.)	0.204	0.174	0.238	0.167	0.138	0.118	0.062	0.031	0.021
15 ©$_z$ (corrected for w. j.)	3.242	3.506	4.250	5.410	5.396	5.315	4.386	3.301	2.598

Table 10.

Location:	Junk Bay (3)	Mean water depth (*H*):	9.91
Course (odd runs):	329	Static mean draft (d_m):	1.52
Course (even runs):	149	Depth/draft (H/d_m):	6.52
Start displ.:	90.11	LCG:	8.29 % aft
Static w.l. length (m):	24.62	Static trim angle (degrees):	0.88

As-recorded data								
0 Run no.	1 & 2	3 & 4	5 & 6	7 & 8	9 & 10	11 & 12	13 & 14	15 & 16
1 Ship speed (knots)	10.55	12.40	13.72	15.82	16.68	17.66	21.98	25.41
2 Mean shaft (rev./min)	449.5	545.0	645.0	757.8	789.5	814.0	894.3	981.3
3 Total mean power (kW)	234.0	441.5	767.0	1237.5	1382.0	1473.5	1703.5	2113.5
4 Displacement	90.11	90.08	90.04	89.98	89.92	89.85	89.76	89.67
5 Rack setting	8.5	9.1	11	12.5	12.9	13.5	14.15	14.75
6 Dynamic trim (degrees)	0.43	0.60	1.64	3.05	3.35	3.46	2.78	2.86
7 Mean speed log (knots)	10.10	11.94	13.10	14.96	15.89	16.70	21.01	24.07
Analysed data								
8 K_Q x 10	0.428	0.453	0.475	0.472	0.466	0.454	0.395	0.371
9 Open water eff. (η_o)	0.582	0.563	0.544	0.546	0.551	0.563	0.601	0.611
10 Advance coeff. (*J*)	0.692	0.652	0.616	0.620	0.630	0.651	0.740	0.774
11 Wake fraction (w_t x 10)	0.447	0.715	0.617	0.378	0.339	0.278	0.245	0.316
12 Froude no. (F_n)	0.349	0.411	0.454	0.524	0.552	0.585	0.728	0.841
13 © overall	3.312	3.723	4.615	4.877	4.692	4.309	2.760	2.255
14 *d* ©$_z$ (due to w.j.)	0.197	0.194	0.242	0.132	0.100	0.072	0.024	0.027
15 ©$_z$ (corrected for w.j.)	3.115	3.529	4.374	4.745	4.592	4.237	2.736	2.228

Table 11.

Location:	Junk Bay (1)	Mean water depth (*H*):	10.52
Couse (odd runs):	329	Static mean draft (d_m):	1.64
Course (even runs):	149	Depth/draft (H/d_m):	6.41
Start displ.:	102.18	LCG:	6.65 % aft
Static w.l. length (m):	24.7	Static trim angle (degrees):	0.43

As-recorded data								
0 Run no.	1 & 2	3 & 4	5 & 6	7 & 8	9 & 10	11 & 12	13 & 14	15 & 16
1 Ship speed (knots)	10.35	12.10	13.67	15.19	15.61	16.17	19.07	22.29
2 Mean shaft rev./min	449.0	536.3	640.8	760.5	785.3	809.8	885.0	944.3
3 Total mean power (kW)	244.0	434.0	770.0	1322.0	1455.0	1578.5	1917.0	2119.5
4 Displacement	102.18	102.16	102.11	102.04	101.95	101.85	101.74	101.63
5 Rack setting	9	9.25	10.45	13	13.2	13.9	15.15	15.85
6 Dynamic trim (degrees)	0.10	0.60	1.22	2.71	3.04	3.33	3.56	3.07
7 Mean speed log (knots)	8.96	10.68	12.08	13.42	13.76	14.16	17.09	19.79
Analysed data								
8 K_Q x 10	0.448	0.467	0.486	0.499	0.499	0.493	0.459	0.418
9 Open water eff. (η_o)	0.568	0.551	0.534	0.518	0.519	0.525	0.558	0.588
10 Advance coeff. (*J*)	0.661	0.628	0.598	0.571	0.574	0.583	0.642	0.707
11 Wake fraction (w_t x 10)	0.709	0.982	0.918	0.738	0.644	0.540	0.347	0.296
12 Froude no. (F_n)	0.342	0.401	0.453	0.503	0.517	0.535	0.631	0.738
13 © overall	3.282	3.545	4.228	5.135	5.221	5.158	4.062	2.966
14 *d* ©$_z$ (due to w.j.)	0.183	0.164	0.221	0.143	0.125	0.104	0.042	0.021
15 ©$_z$ (corrected for w.j.)	3.099	3.381	4.008	4.992	5.096	5.054	4.020	2.945

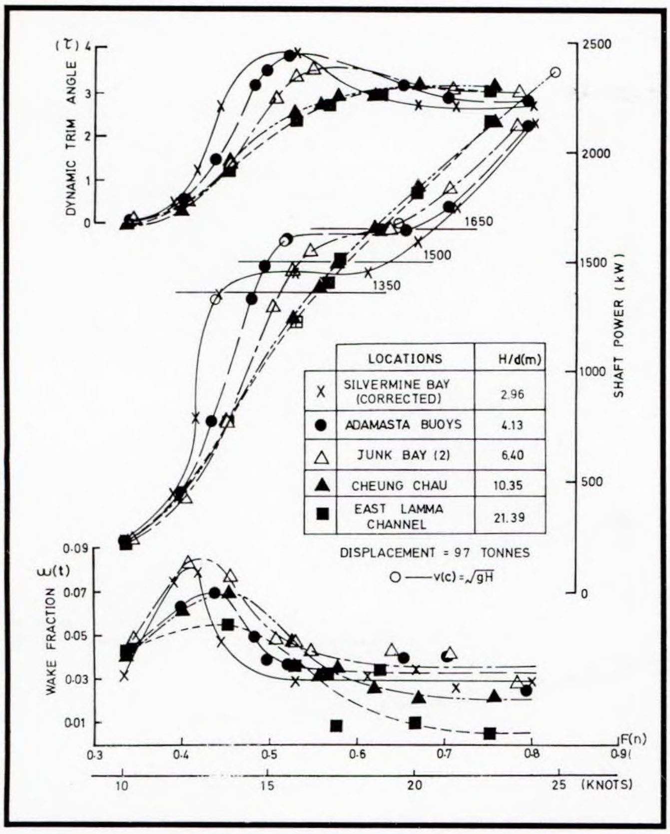

Fig. 6. Power, w_t and dynamic trim angle against speed and F_n at varying H/d_m ratios

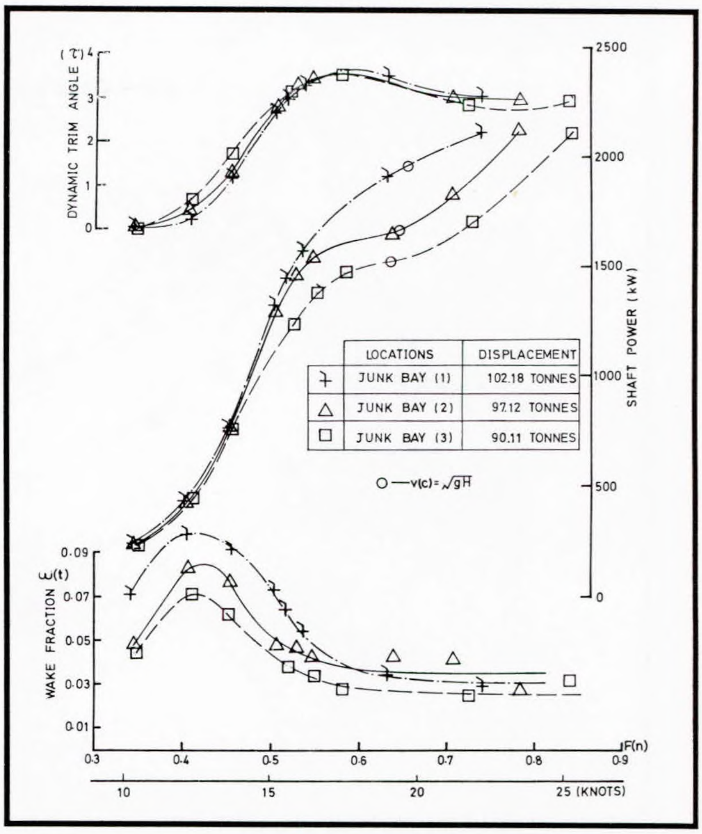

Fig. 7. Power, w_t and dynamic trim angle against speed and F_n at varying displacements

average value was ± 2%. If 'A' brackets were fitted the δ $©_{app}$ on the same calculation basis would be 0.014. This is in line with the findings of Silverleaf & Marwood[21] although their average figure was probably intended for 'A' bracket fittings.

Although there is a random spread of length and Ⓜ in the base data used for Fig. 11, no correction, other than described above, has been made to the $©_{app}$ values for these other parameters. This can be left to individual designers when applying the full-size propulsion coefficient of η_z described more fully below. Thus design power requirements in deep water at any practical L/B and particular F_n, over the range covered by the data, may be expressed as follows:

$$P_S = \frac{©_{app} V_S^3 \Delta^{2/3}}{579.7} \times \frac{1+x}{\eta_p} \times \frac{1}{\eta_o \eta_s}$$

Full-size propulsive coefficient. The components of the expression

$$\left(\frac{1+x}{\eta_p}\right)$$

which is termed here as η_z are well known and it is not possible to deduce them accurately without some means of measuring torque and thrust simultaneously.

Fig. 10 has therefore been produced based on the analysis of the trial results in this paper showing $©_z$, which includes appendages, roughness allowance and η_z, against varying F_n and H/d_m values. Thus design power requirements at varying H/d_m ratios over the F_n given maybe expressed as follows:

$$P_S = \frac{©_z V_S^3 \Delta^{2/3}}{579.7 \eta_o \eta_s}$$

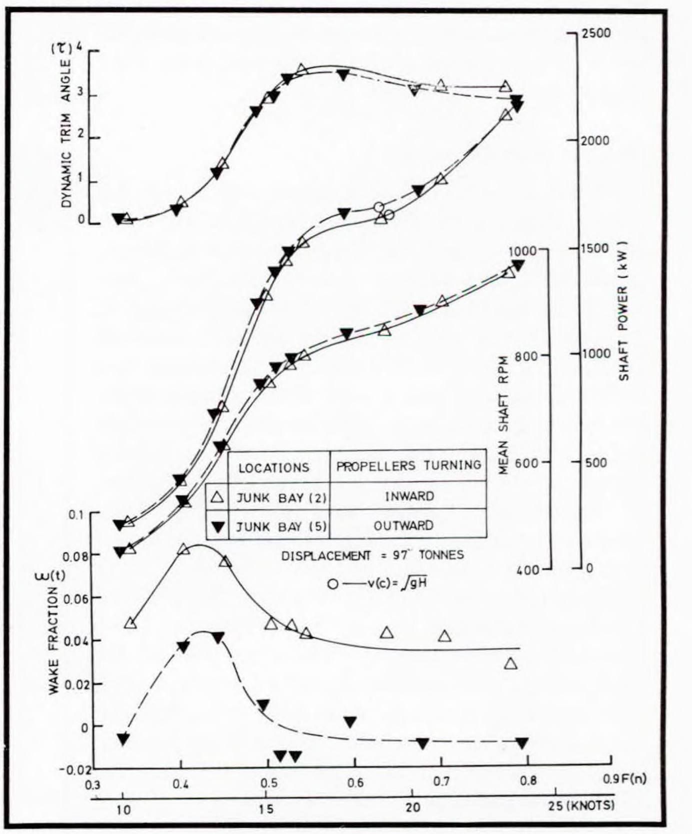

Fig. 8. Power, w_t, rev./min and dynamic trim angle against speed and F_n for inward- and outward-turning propellers

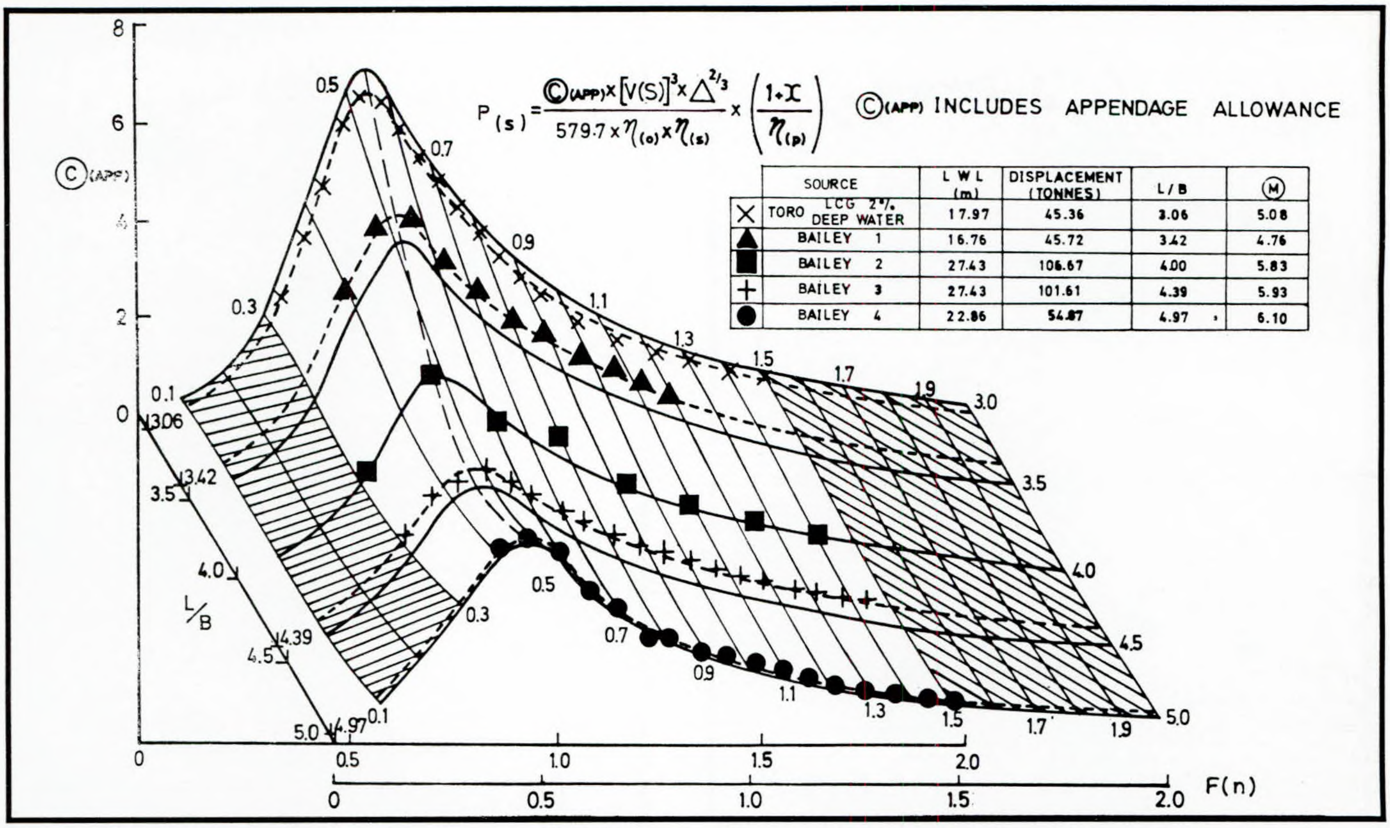

Fig. 9. Deep water $©_{app}$ values versus Froude number F_n at varying *L/B* ratios from Bailey[8] and Toro[9]

Alternatively this data may be used to obtain the relative difference in power requirements between deep water and any particular depth/draft ratio for application to any proprietary deep water data other than those published here.

Discussion of results

Silvermine Bay. It is necessary to discuss the results obtained at Silvermine Bay in some detail and to assist in this, the actual detailed readings, taken during the trials on that location, are reproduced in Appendix 1. The object of running at Silvermine Bay was to use as shallow water as possible conducive with safety. The Silvermine Bay distance had two fixed, known markers, was consistently shallow over most of the length, and was well-fished which gave reassurance concerning hidden obstructions under water due to random dumping.

Correction of Silvermine Bay results. From observation of the speed log and power readings it was generally possible to see where the effect of the gulley at the western end took place. The shallow readings are marked with an 'S' in Appendix 1 and coincidentally the steady shallowest part of the course occurred for approximately 1 nautical mile. The speed log readings were used to correct the mean speed over the whole distance to give values for the H/d_m=2.96 section of the Silvermine location. Thus corrected mean speed is given by:

$$V_N = \frac{V_{SH}\ V_S}{V_L}$$

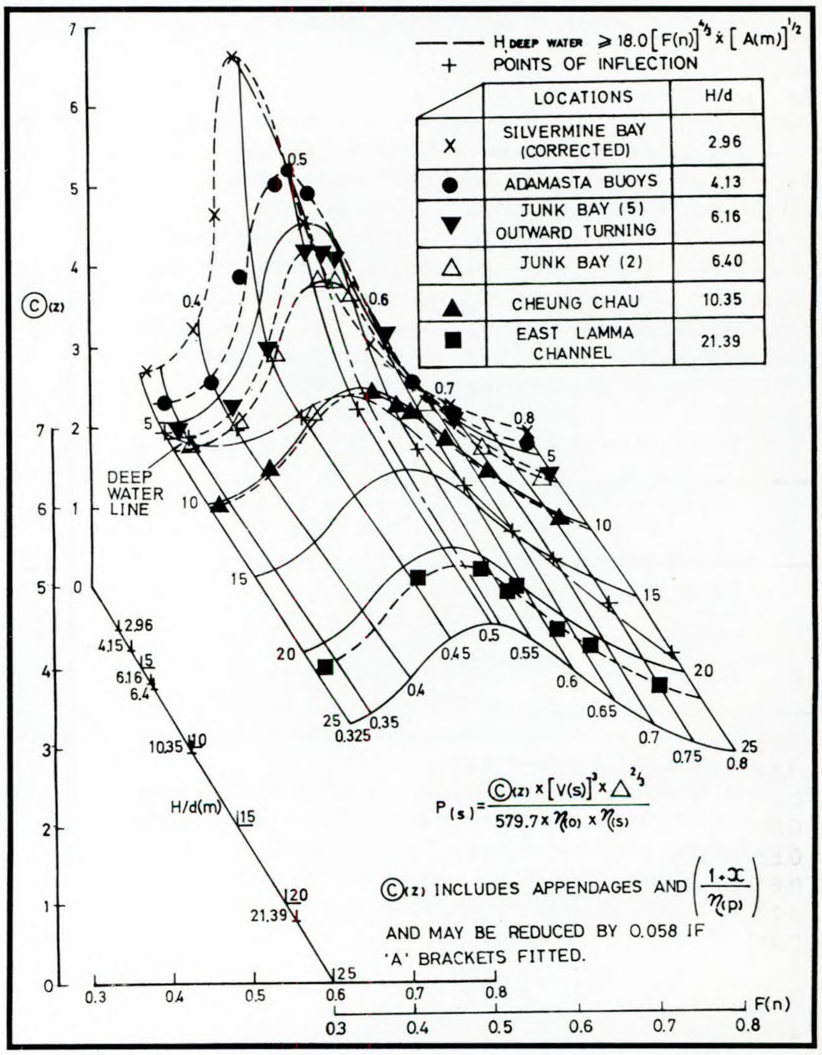

Fig. 10. $©_z$ versus Froude number F_n at varying H/d_m ratios

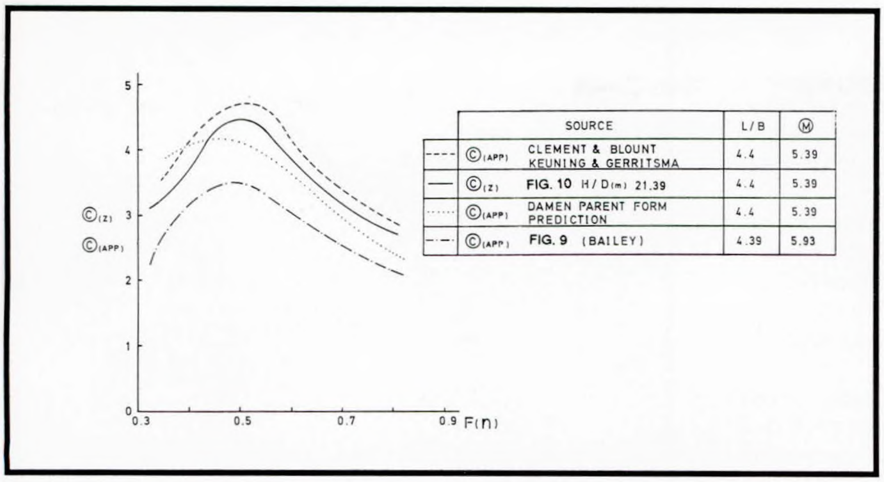

Fig. 11. $©_{app}$, $©_z$ **and** η_z **against** F_n

where:

V_N=vessels corrected overground mean speed for H/d_m=2.96 section only;

V_{SH}=mean of speed log readings over H/d_m=2.96 section only;

V_L=mean of speed log readings overall;

V_S=observed vessels overground mean speed overall.

By the same token the readings for rev./min and power over the H/d_m=2.96 section considered were averaged and used in Table 4.

Full-size and overall propulsive coefficient. As noted in the section above it is proposed to introduce a full-size propulsive coefficient η_z which combines all factors in one, with the exception of the open water efficiency η_o. This factor has been incorporated into, or to be more accurate not isolated from, the data shown in Fig. 10.

Reliable published component data for η_z are scarce, but Fig. 11 shows a comparison with $©_z$ deep water taken from Fig. 10 and $©_{app}$ values taken from Fig. 9, effectively Bailey[8], Damen 'Parent'[23], Clement & Blount and Keuning & Gerritsma interpolation[19, 20]. Table 12 then shows the resulting η_z values for these sources of $©_{app}$ in addition to the suggested mean η_z from ref. 8. As will be seen there is considerable scatter in the data reflecting the various model tank environments.

Data from the Clement[19] interpolation, for the selected L/B used, clearly allows an accurate prediction and more to the point accurately defines the shape of the resistance coefficient curve over the whole range considered. Both the Damen 'parent'[23] and Bailey[8] data require use of η_z. Moreover the recommended Bailey η_z mean line would lead to underestimation of power requirements especially through the hump with bossings or 'A' brackets fitted. Other sample data given by Bailey[8] imply a higher η_z which agrees more closely with Table 12 column 3, particularly through the hump.

A re-examination of existing random tank data may be in order, so that it is presented on the basis of H/d_m, B/D, inward- and outward-turning propellers which, as shown in this paper, all affect significantly w_t and hence η_h, η_r, probably $(1+x)$ and therefore η_z.

The overall propulsive coefficient therefore is given by:

$$\text{OPC} = \frac{\eta_z}{\eta_o}$$

In the data presented in this paper since η_z is incorporated in $©_z$, therefore only additional η_o data are required to make performance predictions.

Outward/inward turning propellers. Through most of the speed range, Fig. 8 indicates that inward-turning propellers appear to have better overall efficiency. This is in spite of a significant reduction in wake with an outward-turning propeller and a generally better open efficiency, although, as frequently happens, overall efficiency is clearly worse until F_n=0.75. It should be noted also that 0.08 t less fuel was used on the inward-turning propeller trials.

Surfing and theoretical critical speed. The speed at which theoretically the wave of translation occurs is given by the following well-known equation:

$$v_c = \sqrt{gH}$$

and is popularly considered to occur at the point of inflection of the power curve.

It appears from Fig. 6 that a more readily definable point at which to determine passage through the speed of translation would be the point of maximum dynamic trim.

In some full-scale and corresponding model trials reported by Bailey[4], the speed of translation was given as $0.9\sqrt{gH}$. The latter conclusion was based however on a peak 'camel' hump of corresponding model resistance data that was not obvious from the full-scale information given.

When the decision to conduct the tests in this paper was taken, in addition to the main objective of putting raw full-scale data before the profession, we were looking for indications of the 'camel' hump referred to above and shown in a number of papers on this subject among which are refs. 4, 14 and 16. Our conclusion is that whilst this may happen in model resistance tests, it does not occur in practice when the 'sea' is unrestricted in width and a propulsion device is fitted. This may be due to all or any combination of the following.

(1) Increased dynamic trim and hence sinkage and wake caused by a 'bore' effect on the wave of translation and its lon-

Table 12. η_z **against** F_n **for various** $©_{app}$ **sources**

F_n	Bailey ref.[8] Mean line	Bailey (Fig. 9)	Damen Parent form[23]	Clement & Blount[19], Keuning & Gerritsma[20]
0.35	1.22	1.22	0.85	0.91
0.40	1.21	1.18	0.91	0.90
0.45	1.21	1.25	1.03	0.94
0.50	1.20	1.28	1.09	0.95
0.55	1.21	1.30	1.10	0.94
0.60	1.21	1.29	1.07	0.93
0.70	1.23	1.24	1.06	0.93
0.80	1.26	1.27	1.13	0.95
Range average	1.22	1.25	1.03	0.93

gitudinal position relative to the transom, due to the finite restrictive width of model tanks.

(2) The ability to test a model, not being self-propelled, at any given speed during passage of the wave of translation.

(3) The absence of propellers, particularly with respect to increased dynamic trim and sinkage that would affect power requirements.

Incidentally, on trials no obvious broad wave of translation at 90° to the hull forward of the transom as shown in a photograph accompanying ref. 7 was observed. Much rather a large 'wide' wave formed tending towards 90° to the ship centre-line in the critical speed region, but this was aft of the transom.

In Fig. 6 the corresponding points of theoretical $v_c=\sqrt{gH}$ have been plotted on the various power curves, from which it will be noted that additional power is required to traverse the point of inflection or actual critical speed on the two shallowest power curves.

The reason for this is not only an increase of resistance but also the fact that theoretical v_c comes in phase with the peak of τ, sinkage and wake, with the associated loss of propulsive efficiency, thus requiring an augment of power. However, when the point of inflection is passed, a rapid gain in speed results for minimal additional power, accompanied by a sharp drop in wake, which we propose to term the 'surfing effect'.

Fig.12 shows a comparison of theoretical critical speed with water depth (*H*) and speed of the actual points of inflection for data in this paper and data taken from refs. 1, 2 and 25. The 'King Class' 97 t data indicate that $v_c=\sqrt{gH}$ will only occur at $H/d_m=4.65$.

By reference to Fig. 6 it can be proposed that 'surfing' will then occur when actual critical speed $v_c \geq \sqrt{gH}$, and it may further be observed that 'surfing' is likely to be associated with a significant 'hump' in the dynamic trim curve τ . In short, a surfing wave is generated when $v_c \geq \sqrt{gH}$, and further, the depth/draft ratio at which this happens will probably be unique for each type of vessel.

It is unfortunate that in Fig. 1 the mean drafts associated with the specific trials are generally not given although the same trends maybe be observed with, apart from the *Makrelen* 118 t, the point at which $v_c=\sqrt{gH}$ is in the region of $H/D_m=5.0$.

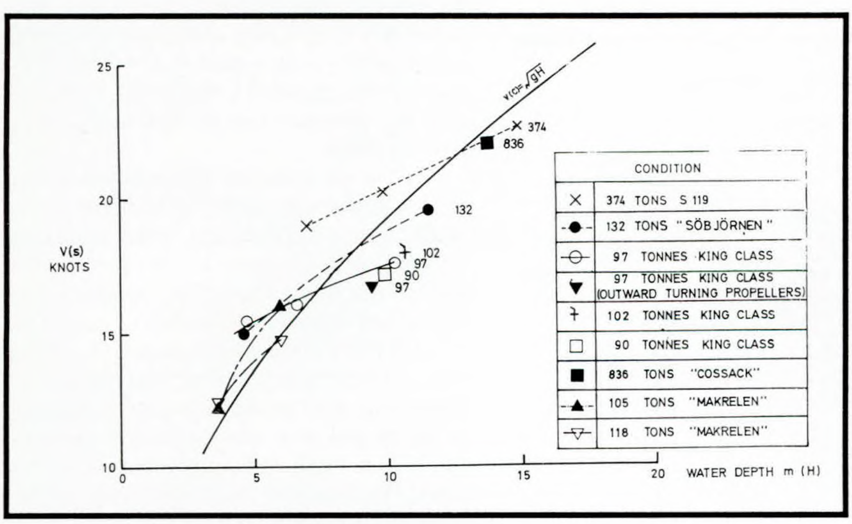

Fig. 12. Comparison of theoretical critical speed and full-scale speeds for power curve points of inflection

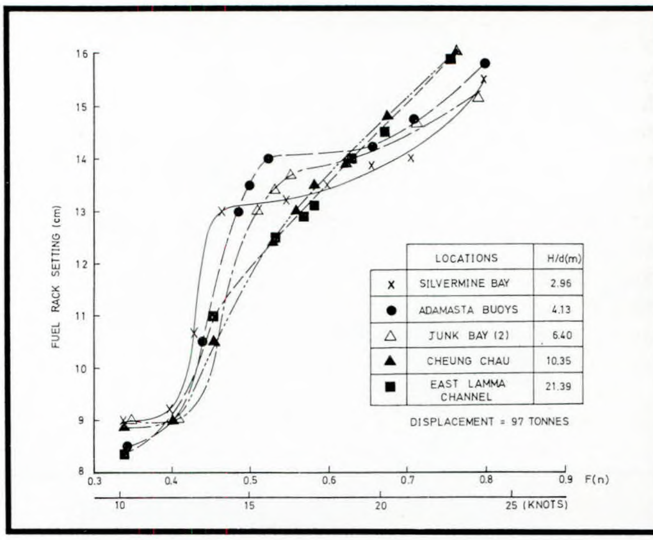

Fig. 13. Mean fuel rack setting against speed and F_n at varying H/d_m ratios

Clearly more work is required to develop this proposition, particularly any effect of a smooth or undulating sea bottom profile but it is hoped that this will explain the cause of the rapid increase in speed for virtually no additional power observed on full-scale trials in relatively shallow water immediately following the hump transition.

Depth/draft point of maximum hump power requirement. Notwithstanding the above, maximum hump power requirement will decrease after a certain point is reached as the water depth decreases. This interesting phenomena, observed also in refs. 1 and 25, occurred in the present trials on the shallowest location at Silvermine Bay. Our first reaction was to question the torsion meter and speed results, but these have been thoroughly checked and found to be correct. However, as a cross-check the mean engine rack settings were then plotted against F_n for all locations and these are shown in Fig. 13. Rack settings give a fairly accurate indication of torque output of the engine and hence, in conjunction with rev./min, are a good indication of power trends. They are, moreover, quite independent of speed and shaft torsion meter readings and it can be seen that the same trends occur as in Fig. 6.

As may be noted from Fig. 10, the resistance factor $©_z$ continues to increase, when in shallow water, in a progressive manner with decrease in H/d_m. Therefore some other effect must be at play to cause the apparent more efficient performance. Fig. 14 shows, for each location tested, the ratio of power at the location against deep water requirements at corresponding F_n. It can be seen that up to $F_n=0.5$ the power required increases as H/d_m decreases. In fact prior to traversing the speed of translation this can be in excess of double deep water requirements at low H/d_m values. However, at $F_n=0.5$ this situation changes, at which point the reduction in power requirements due to a lower v_c become more than the resistance coefficient increase and reduction in propulsive efficiency due to shallow water. In Fig. 15 the function $©_z \times F_n^3$ at the points of maximum $©_z$ against F_n are shown.

In conjunction with η_o the function $©_z \times F_n^3$ is an indication of power required and it may be seen that maximum or worst case hump translation occurs at H/d_m=5.0, very close in fact to the point at which $v_c=\sqrt{gH}$, as discussed in the Surfing and theoretical critical speed section. This point is dramatically demonstrated in Table 13 which shows speeds attainable with this vessel had it only been fitted with 1500 kW. For these purposes a constant power characteristic has been assumed. It will also be noticed from Fig. 6 that had the vessel an installed power of 1350 kW and below, the best results would have been obtained in the deepest water possible, whereas with 1650 kW and above the reverse would be the case, conducive with the practical consideration of bottom clearance safety.

Therefore, in general, where trials or operation in shallow water are requested and the installed power will result in a speed falling in the F_n range of 0.5 to 0.6, it is recommended to avoid H/d_m conditions between 3.5 and 6.0 or adjust installed power or craft dimensions to avoid this region.

Shallow water effect. To be clear of shallow water effect Millward[7] and Lackenby[11] give, respectively:

a) 'One boat length' (Note this was also suggested by Taylor[24].)

b) $$\frac{\sqrt{A_m}}{H} < 0.18$$

In the case of the 'King Class' vessels this equates to depth/draft ratios of 15.47 and 7.91 respectively at the 97 t condition.

Shallow water effect for this type of craft may be said to have ceased when the resistance coefficient $©_z$ becomes sensibly constant. It may be seen from Fig. 10 that points of constant $©_z$ increase with F_n so that Lackenby's formula[11], in its present form, intended for large vessels at relatively low F_n values, is not suitable for planing craft. We propose the following formula for describing the point at which shallow water ceases to have an effect on the performance of semi-planing craft. It may also be used for clearance required between model and tank boundaries.

$$H_{\text{Deepwater}} = 18.0\, F_n^{4/3} \sqrt{A_m}$$

The proposal by Millward[7], however, described by him as 'a rule of thumb', can certainly be said to be safe and useful for situations where detailed information on the hull is not available.

Wake and the 'finite bottom effect'. The most unexpected results of the tests were the wide variation in wake that occurred not only over the speed range considered but also in the various H/d_m locations and displacements tested. Values of w_t are shown against corresponding F_n, power and dynamic trim angle in Figs. 6, 7 and 8, in Fig. 16 against H/d_m on lines of constant F_n and against the ratio of deep to shallow water in Fig. 17, all at the 97 t condition (except Fig. 7).

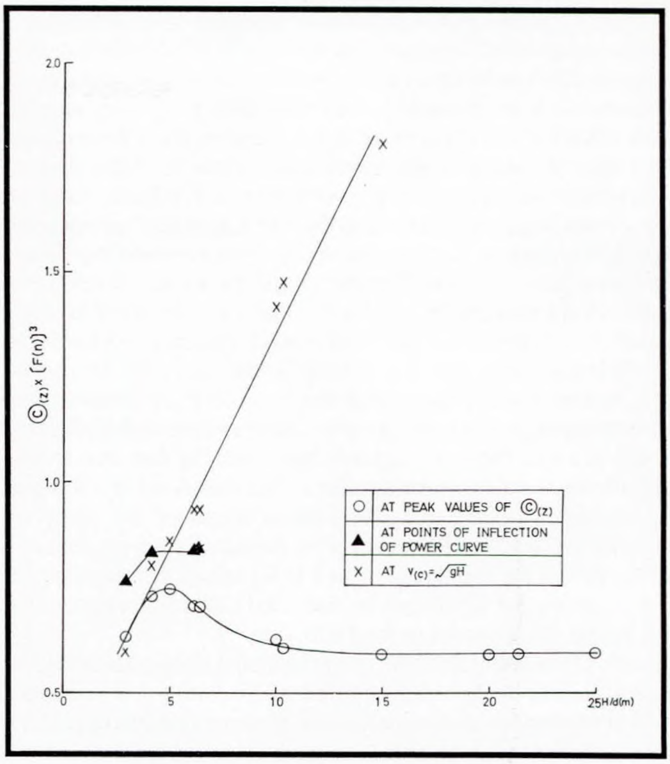

Fig. 15. Power function ($©_z \times F_n^3$) against H/d_m

The following observations may be made. A progressive increase in wake will occur peaking in the F_n range of 0.4–0.45 due to increased immersion of the stern. With respect to this, both Bailey[13] and Millward & Bevan[16] showed that on this type of vessel increased immersion or sinkage will occur during passage of the hump region. Furthermore Fig. 7 shows a progressive increase in w_t as draft increases.

For those runs where the vessel was most affected by the wave of translation (Silvermine Bay, Adamastar and Junk Bay) maximum w_t occurred at about 0.8 F_n of that at which dynamic trim peaked, suggesting that wake is mostly influenced by the ship-generated wave system and associated sinkage. The peak wake is independent of the wave of translation, but influenced increasingly by it as the water depth decreases and it comes in phase with, and augments, dynamic trim and sinkage. It may then be seen that the peak wake, and incidentally dynamic trim, in the hump region tends to occur slightly earlier as depth/draft ratio decreases.

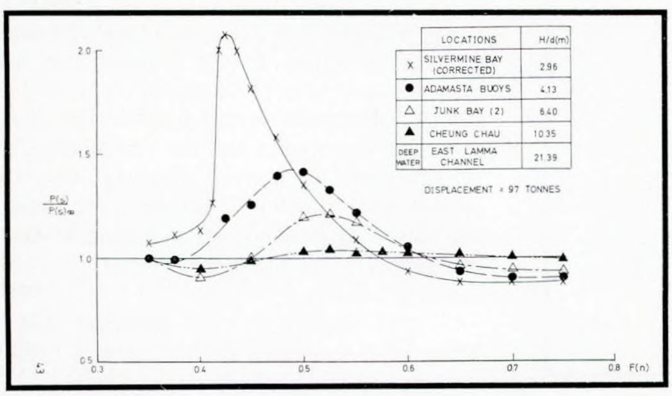

Fig. 14. Ratio of shallow/deep water power at varying H/d_m against F_n

Table 13. Performance in hump region at 1500 kW as a function of depth/draft ratio

H/D_m	Max. speed (knots)	Hump traversed
Deep water	17.65	Yes
10.35	17.35	Yes
6.40	15.80	No
4.13	14.80	No
2.96	19.10	Yes

Fig. 17 shows that w_t reaches a maximum over almost the whole speed range considered at about H/d_m=6.0, an increasing Venturi effect then occurs as the craft comes in closer proximity with the bottom. A marked drop in w_t does happen compared with other locations below H/d_m=6, particularly at Silvermine Bay after the point of maximum wake is passed. This is quite apart from the wake reduction associated with a lighter draft as the vessel begins to plane and the 'surfing effect' previously noted. We propose to term this Venturi phenomenon the 'finite bottom effect'. Outward-turning propellers have a lower wake than inward-turning, the effects of which are discussed in more detail in the section on outward/inward turning propellers.

We conclude that the 'unexplained' increase in power requirements which have been observed on many commercial trials and put down to increased resistance of the hull in shallow water prior to the hump speed, have been in fact due to the significant wake increase, similar to that shown in Figs. 6, 7 and 8, coming in phase with the critical speed of the wave of translation. What in effect happens is that where a propeller is designed for an operational speed at F_n values in excess of 0.6 it will encounter significantly increased wake when traversing the hump. This results in the following.

(1) In addition to the propeller being over-pitched due to normal under-design speed operation, the hump wake increase will further move the propeller and power available into a less efficient zone.

(2) The double-negative effect of (1) will reduce the rev./min and hence the effective power available.

(3) Furthermore, most patrol boat engines are less efficient and have less maximum torque available when running 'off' the design rev./min so that a further loss in rev./min will occur due to less torque availability, thus reducing still further the available power and propulsive efficiency.

(4) This whole effect is further aggravated if the propeller design is made for a light displacement in deep water and further trials or operation are carried out at a greater displacement in shallow water.

Any improvement in the wake regime therefore will not only improve the efficiency of the propeller but also the main engines.

The only solution to this inherent, poor situation is either to seek means to reduce the sinkage effect during passage through the hump, or have sufficient reserve power not to be bothered by it.

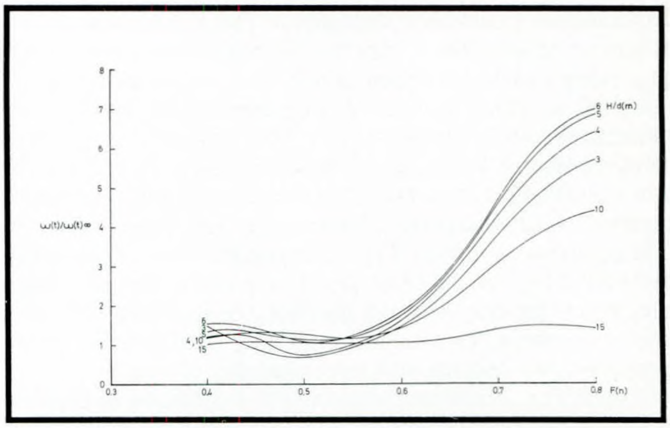

Fig. 17. $w_t/w_{t\infty}$ ratio against F_n at varying H/d_m values

Clearly, trim flaps and wedges, which in some quarters are considered to reduce resistance, in fact reduce sinkage and hence wake thus improving the propulsive efficiency and useful power available. Furthermore, the trials with and without the jet aperture showed that 'contamination' of the planing surface causes increased dynamic trim, sinkage and hence wake and power requirements. It should be pointed out that this is not a condemnation of fitting a jet but only describes the effect on performance when the jet installation is left to idle and becomes merely a 'hole' in the hull planing area.

When working, the jet helps to boost the vessel through the hump and, if correctly designed and applied, gives useful augmentation to top speed.

CONCLUSION

In displaying the results an effort has been made to minimize the amount of additional data required to perform at least a first estimate of performance in any particular set of trial circumstances given that some sufficiently reliable open water charts for the propeller design of flat-face aerofoil section-type propellers are available. Care must be taken when using other propeller section types and blade shapes, and/or theoretical design programmes, as this may affect the wake values.

It should be borne in mind that this paper describes one type of hard chine semi-planing vessel with one type of propeller and appendage configuration. It will nevertheless be clear, as the results of this paper show, that a number of interactive parameters affect the design of a propeller and the corresponding performance of a semi-planning vessel. Trends, therefore, which appear in this paper that can be expected on other designs of hull and propeller for this type of craft, may be stated as follows.

(1) Wake will vary noticeably with sinkage and decreasing B/d as well as over the speed range on either side of the hump.

(2) As the water depth decreases the point of the critical speed of translation will

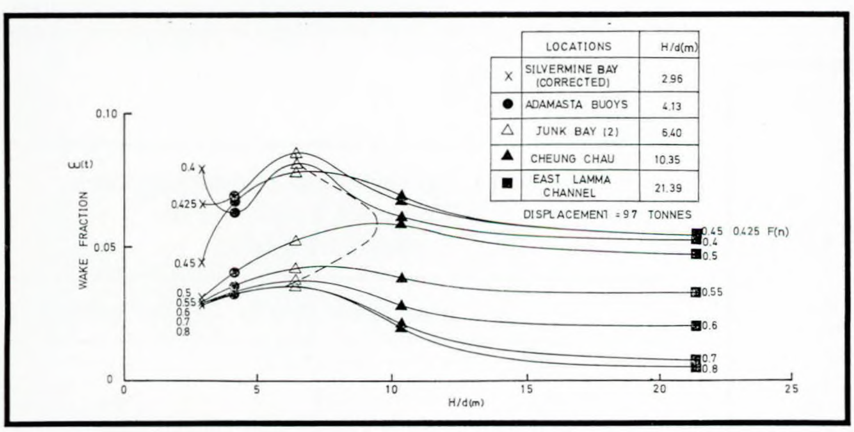

Fig. 16. w_t values on lines of constant F_n against H/d_m

decrease and come in phase with the points of maximum dynamic trim and hence affect sinkage, wake and power required to traverse this region.

(3) Contamination of the hull planing area aft of the LCG should be avoided, provided in so doing other important parameters such as sea keeping, manoeuvring shallow water hull protection and performance boost arrangements are not unacceptably affected.

(4) Any system with low drag that effectively reduces dynamic trim and sinkage will have a beneficial effect on performance through the hump range.

(5) Inward-turning propellers have a better overall efficiency but have a higher wake than outward-turning propellers up to F_n=0.75.

(6) Because of interaction between peaks of other parameters, particularly in low H/d_m ratios, the theoretical $v_c=\sqrt{gH}$ is just that, theoretical, except at one value of F_n and depth/draft ratio for each type of vessel. It probably more properly defines the point at which the ship-generated wave system becomes suitable for surfing. This point does however indicate the area of least favourable trial depth/draft ratio for hump translation.

(7) The depth at which shallow water effect ceases, increases as Froude number increases and there seems to be no reason why the formula proposed here by the author should not be used for other craft.

(8) The simple parameter, dynamic trim, which is easy to measure on trials, can be used to indicate the point of actual critical speed of translation and its form will indicate when 'surfing' can be expected.

These conclusions confirm our view that the practice of measuring the resistance of the hull and wake analysis etc. during a pure resistance test without the presence of the propulsor is misleading. The propulsor type i.e. blade sections shape, pitch distribution, rotational direction, position, hull shape, form of appendages and water depth are clearly interactive. They all have an effect on the working environment of the propulsor and hence the overall efficiency of the vessel and it's propulsion machinery. Any tests which are carried out, whether model or full-size, should be done when all influences on the vessel, particularly the wake, are operating. This will give the most reliable information for optimizing a vessel's performance and propulsor design, for minimizing cavitation, and for future development.

Hadler[15], in the conclusion to his paper on the subject, stated "In optimizing the design of high-performance planing craft the whole hydrodynamic system must be considered"; a view with which we entirely agree for any type of vessel including that described in this paper. From a practical design point of view the remarks made by Noordenbos & Van Den Bosch[17] are also worthy of note.

The results show, especially around the hump speed in various depths of water, that a number of factors are at work which cannot be adequately covered by the present fashionable wave resistance theories. Some rethinking will be required on the model testing and theoretical approach to fast patrol boat design and evaluation in the following areas:

(1) wake variation at different water depths;

(2) effect on wake due to: blade section shapes and propeller rotation; beam/draft, depth/length and depth/draft ratios; finite bottom effect; surfing effect;

(3) the method of measuring wake to be performed during a self-propulsion test (It is appreciated there are technical difficulties doing a full wake analysis over the propeller disc when running self-propulsion tests, but this is likely to be the only method that will produce reliable results.);

(4) both the proposals for finite bottom and surfing effects will need more study, particularly on theoretical power prediction methods for this type of craft (In this respect the unique point in practice where $v_c=gH$ appears to have significance with respect to maximum wake and power requirements through the hump. This clearly needs more investigation which may be possible through re-analysis of existing data.);

(5) the effect on model predictions when a finite tank boundary exists (In this respect it is pleasing to note that Millward & Bevan[16] have made some study of this, but they did not touch on the effect of wake variation.);

(6) present prediction theory to be reconsidered and to combine resistance and propulsion factors.

In many respects the shipbuilding industry itself is to blame for not carrying out or presenting comprehensive full-size data to allow the research fraternity basic information on which to determine their future direction. This should cover commercial test data evaluation and presentation, as well as the parameters now required on any future theoretical approach. It is regrettable however that Rasmussen's[1] and later Hadler's[15] leads were not followed up, at least in published form, by treating the question of semi-planing boat performance parameters as an interdependent whole. This paper seeks in a way to rectify this state of affairs by highlighting points for the further development and direction of this subject as well as presenting data that hopefully will be of use to the designer.

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APPENDIX 1
SILVERMINE BAY SHALLOW WATER CORRECTION

RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS																	
			SHALLOW	S	S	S	S	S	S	S	S	S	S	S							
			S.LOG	9.7	9.8	9.8	9.5	10.2	9.8	10	9.9	10	10.1	9.7	10	10	10	9.9	10	9.9	9.7
		PORT	REV/MIN	442	424	442	442	442	442	443	443	443	443	443	443	444	444	444	444	444	444
			POWER	118	118	118	118	118	118	118.5	118.5	118.5	118.5	118.5	118.5	118	118	118	118	118	118
1	260																				
		STBD	REV/MIN	445	445	445	445	445	445	445	445	445	445	445	445	444	444	444	444	444	444
			POWER	113	113	113	113	113	113	113	113	113	113	113	113	111.5	111.5	111.5	111.5	111.5	111.5
RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS																	
			SHALLOW									S	S	S	S	S	S	S	S	S	S
			S.LOG	9.9	9.9	9.9	9.5	9.9	10.1	10	9.6	9.8	10	9.6	10	9.6	10.1	9.9	10	9.8	9.6
		PORT	REV/MIN	447	447	447	447	447	447	447	447	447	447	447	447	448	448	448	448	448	448
			POWER	121	121	121	121	121	121	120	120	120	120	120	120	120	120	120	120	120	120
2	80																				
		STBD	REV/MIN	444	444	444	444	444	444	444	444	444	444	444	444	444	444	444	444	444	444
			POWER	112	112	112	112	112	112	111.5	111.5	111.5	111.5	111.5	111.5	111	111	111	111	111	111
RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS																	
			SHALLOW	S	S	S	S	S	S	S	S	S									
			S.LOG	12	11.4	11.4	12	12	12	11.6	12	12	12	11.9	11.6	11.8	11.8	12.1	12.1	11.8	
		PORT	REV/MIN	542	542	542	542	542	542	542	542	542	543	543	543	543	544	544	544	544	
			POWER	230	230	230	230	230	230	230	230	230	233	233	233	233	234	234	234	234	
3	260																				
		STBD	REV/MIN	540	540	540	540	541	541	541	541	541	539	539	539	539	541	541	541	541	
			POWER	218	218	218	218	220	220	220	220	220	217	217	217	217	216	216	216	216	
RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS																	
			SHALLOW								S	S	S	S	S	S	S	S	S		
			S.LOG	11.9	11.5	12.5	12	12	12.3	12	11.6	11.6	11.8	11.6	12	11.5	11.5	11.6	12		
		PORT	REV/MIN	544	544	544	544	544	543	543	543	543	543	543	543	543	543	543	543		
			POWER	235	235	235	235	235	232	232	232	232	232	232	230	230	230	230	230		
4	80																				
		STBD	REV/MIN	540	540	540	540	540	540	540	540	540	540	540	540	540	540	540	540		
			POWER	219	219	219	219	219	218	218	218	218	218	218	216	216	216	216	216		
RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS																	
			SHALLOW	S	S	S	S	S	S	S	S	S									
			S. LOG	12.3	13	12.7	12.5	13	12.5	12	12.5	12.2	12.3	13	12.8	13	13	13.2			
		PORT	REV/MIN	641	641	641	641	641	641	641	641	641	641	641	641	645	645	645			
			POWER	398	398	398	412	412	412	417	417	417	405	405	405	396	396	396			
5	260																				
		STBD	REV/MIN	640	640	640	638	638	638	638	638	638	637	637	637	641	641	641			
			POWER	380	380	380	387	387	387	389	389	389	384	384	384	369	369	369			
RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS																	
			SHALLOW								S	S	S	S	S	S	S	S			
			S.LOG	13.1	13.4	13.5	12.9	12.9	13	12.5	12	12.1	11.9	12.2	12.6	12.8	12.4	12.2			
		PORT	REV/MIN	642	642	642	642	643	643	643	640	640	640	640	641	641	641	641			
			POWER	396	396	396	396	397	397	397	406	406	406	406	409	409	409	409			
6	80																				
		STBD	REV/MIN	641	641	641	641	642	642	642	639	639	639	639	639	639	639	639			
			POWER	377	377	377	377	376	376	376	394	394	394	394	392	392	392	392			

APPENDIX 1 Continued
SILVERMINE BAY SHALLOW WATER CORRECTION

RUN NO	COURSE	SHAFT	READING	TIME INTERVALS														
			SHALLOW	S	S	S	S	S	S	S	S							
			S.LOG	13	14	13.5	14	13.8	12.8	12.8	12.6	12.6	12.4	13.2	14.2	15	15	14.8
		PORT	REV/MIN	755	755	755	755	755	750	750	750	749	749	754	754	758	760	760
			PORT	681	681	671	671	671	698	698	696	693	693	681	659	659	643	643
7	260																	
		STBD	REV/MIN	758	758	759	758	758	754	754	755	754	754	759	762	762	764	764
			POWER	661	661	664	662	662	683	683	688	693	693	666	639	639	628	628
RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS														
			SHALLOW							S	S	S	S	S	S	S	S	
			S.LOG	13.4	15.2	15.1	15	15	13.7	12.9	12	12.9	12	12.6	13.2	13.2	13	
		PORT	REV/MIN	758	758	751	751	751	751	751	753	753	753	753	752	752	752	
			POWER	639	639	691	691	691	701	701	690	690	682	682	683	683	683	
8	80																	
		STBD	REV/MIN	761	761	755	755	755	754	754	756	756	756	756	754	754	754	
			POWER	632	632	685	685	685	689	689	676	676	688	688	672	672	672	
RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS														
			SHALLOW	S	S	S	S	S	S	S								
			S.LOG	14	13.1	14.7	14	13	14.5	17	17.5	16.2	16.2	16.4	16			
		PORT	REV/MIN	792	792	790	790	791	791	802	802	805	805	801	801			
			POWER	784	784	787	787	787	787	731	731	721	721	746	746			
9	260																	
		STBD	REV/MIN	788	788	787	788	788	797	797	796	796	796	792	792			
			POWER	745	745	753	737	737	676	676	663	688	688	704	704			
RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS														
			SHALLOW						S	S	S	S	S	S				
			S.LOG	14.6	15	16	16	15.1	14	15.6	16.5	17	16.7	15.2				
		PORT	REV/MIN	795	795	800	800	800	799	799	805	805	804	804				
			POWER	759	759	742	742	744	758	758	717	717	726	726				
10	80																	
		STB	REV/MIN	791	791	794	792	792	794	798	798	794	796	796				
			POWER	721	721	710	707	707	683	667	667	679	673	673				
RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS														
			SHALLOW	S	S	S	S	S	S									
			S.LOG	18	18	17.5	17.2	17.2	17.9	17.6	18	16.3	16.9	17				
		PORT	REV/MIN	821	821	820	820	823	823	822	818	818	818	818				
			POWER	750	750	754	754	743	743	744	776	776	773	773				
11	260																	
		STBD	REV/MIN	819	819	818	818	822	822	821	816	816	815	815				
			POWER	718	718	727	727	711	711	708	742	742	734	734				
RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS														
			SHALLOW						S	S	S	S	S	S				
			S.LOG	15.5	15.5	16.9	16.5	16	15.7	18.2	18.2	18	17.2	18				
		PORT	REV/MIN	814	814	818	818	816	816	816	821	821	822	822				
			POWER	813	813	767	767	796	735	735	741	741	757	757				
12	80																	
		STBD	REV/MIN	810	810	817	817	813	821	821	820	820	819	819				
			POWER	772	772	743	743	762	710	710	708	708	716	716				

APPENDIX 1 Continued
SILVERMINE BAY SHALLOW WATER CORRECTION

RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS									
			SHALLOW	S	S	S	S	S	S				
			S.LOG	19	19.6	19.5	19	19.3	19	18.9	19	18	17.5
		PORT	REV/MIN	861	861	858	859	859	859	859	855	855	855
			POWER										
13	260												
		STBD	REV/MIN	857	857	855	857	857	855	855	851	860	860
			POWER	783	783	787	777	777	789	789	826	825	825

RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS									
			SHALLOW						S	S	S	S	S
			S.LOG	18	18.2	17.8	17	19	19	19.8	19.5	19	20
		PORT	REV/MIN	856	856	856	855	855	860	860	861	860	860
			POWER	855	855	874	858	858	821	821	827	827	827
14	80												
		STBD	REV/MIN	853	853	851	852	852	856	856	857	856	856
			POWER	803	803	826	806	806	778	778	778	774	774

RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS									
			SHALLOW	S	S	S	S	S					
			S.LOG	20.8	22	21	20.5	20.7	20.8	21	19.9	19.5	19.7
		PORT	REV/MIN	895	895	892	893	893	894	894	891	888	888
			POWER	896	896	895	890	890	892	892	913	946	946
15	260												
		STBD	REV/MIN	895	895	894	895	895	896	896	889	889	889
			POWER	863	863	866	855	855	865	865	874	907	907

RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS								
			SHALLOW					S	S	S	S	S
			S.LOG	19.5	20.5	20	19.1	20.5	21	20.8	20.2	20.8
		PORT	REV/MIN	893	893	889	890	895	895	895	895	894
			POWER	905	905	933	920	894	894	889	889	900
16	80											
		STBD	REV/MIN	894	894	890	892	895	895	893	894	894
			POWER	870	870	897	873	863	863	853	853	858

RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS								
			SHALLOW	S	S	S	S	S				
			S.LOG	22	23.2	23.9	23.2	23.5	22.4	23.1	22.1	22.6
		PORT	REV/MIN	962	962	962	967	965	965	952	956	956
			POWER	1064	1064	1067	1065	1067	1067	1060	1060	1060
17	260											
		STBD	REV/MIN	972	972	972	980	974	974	962	967	967
			POWER	1072	1072	1073	1081	1077	1077	1065	1072	1072

RUN NO.	COURSE	SHAFT	READING	TIME INTERVALS								
			SHALLOW					S	S	S	S	S
			S.LOG	23.1	22.9	22	23	24	24	23	23.5	23
		PORT	REV/MIN	962	962	955	964	968	968	965	962	962
			POWER	1061	1061	1061	1067	1066	1066	1062	1068	1068
18	80											
		STBD	REV/MIN	972	972	966	977	980	980	975	971	971
			POWER	1074	1074	1075	1084	1080	1080	1080	1075	1075

Appendix 1 Continued
SILVERMINE BAY SHALLOW WATER CORRECTION
MEANS FOR ALL RUNS

MEANS FOR RUN PAIR 1 & 2	S.LOG	REV/MIN	POWER
PORT OVERALL AVERAGE	9.87	445.2	119.3
PORT SHALLOW AVERAGE	9.85	444.9	119.1
STBD OVERALL AVERAGE	9.87	444.3	112
STBD SHALLOW AVERAGE	9.85	444.5	112.1
AVERAGE TIMED SHIP SPEED	10.12		
CORRECTED SPEED FOR SHALLOW	10.1		
MEANS FOR RUN PAIR 3 & 4			
PORT OVERALL AVERAGE	11.85	543	232
PORT SHALLOW AVERAGE	11.76	542.5	230.4
STBD OVERALL AVERAGE	11.85	540.2	217.8
STBD SHALLOW AVERAGE	11.76	540.3	218
AVERAGE TIMED SHIP SPEED	11.92		
CORRECTED SPEED FOR SHALLOW	11.83		
MEANS FOR RUN PAIR 5 & 6			
PORT OVERALL AVERAGE	12.65	641.6	404
PORT SHALLOW AVERAGE	12.41	640.8	408.3
STBD OVERALL AVERAGE	12.65	639.5	383.6
STBD SHALLOW AVERAGE	12.41	638.8	388.9
AVERAGE TIMED SHIP SPEED	12.89		
CORRECTED SPEED FOR SHALLOW	12.65		
MEANS FOR RUN PAIR 7 & 8			
PORT OVERALL AVERAGE	13.55	753.4	678.8
PORT SHALLOW AVERAGE	13.02	752.8	685.1
STBD OVERALL AVERAGE	13.55	757	668.7
STBD SHALLOW AVERAGE	13.02	755.9	674.8
AVERAGE TIMED SHIP SPEED	13.93		
CORRECTED SPEED FOR SHALLOW	13.39		
MEANS FOR RUN PAIR 9 & 10			
PORT OVERALL AVERAGE	15.4	798.6	750.4
PORT SHALLOW AVERAGE	15.02	797.2	757.6
STBD OVERALL AVERAGE	15.4	793.1	701
STBD SHALLOW AVERAGE	15.02	793	700.8
AVERAGE TIMED SHIP SPEED	16.4		
CORRECTED SPEED FOR SHALLOW	16		
MEANS FOR RUN PAIR 11 & 12			
PORT OVERALL AVERAGE	17.18	819.1	761.7
PORT SHALLOW AVERAGE	17.64	820.5	746.7
STBD OVERALL AVERAGE	17.18	817.6	728.7
STBD SHALLOW AVERAGE	17.64	819.8	715
AVERAGE TIMED SHIP SPEED	17.96		
CORRECTED SPEED FOR SHALLOW	18.44		
MEANS FOR RUN PAIR 13 & 14			
PORT OVERALL AVERAGE	18.81	858	842.3
PORT SHALLOW AVERAGE	19.34	859.8	824.6
STBD OVERALL AVERAGE	18.81	855.3	794.4
STBD SHALLOW AVERAGE	19.34	856.3	779.8
AVERAGE TIMED SHIP SPEED	19.61		
CORRECTED SPEED FOR SHALLOW	20.16		
MEANS FOR RUN PAIR 15 & 16			
PORT OVERALL AVERAGE	20.44	892.7	904.5
PORT SHALLOW AVERAGE	20.83	894.2	893.3
STBD OVERALL AVERAGE	20.44	893.4	896.5
STBD SHALLOW AVERAGE	20.83	894.5	859.2
AVERAGE TIMED SHIP SPEED	21.13		
CORRECTED SPEED FOR SHALLOW	21.53		
MEANS FOR RUN PAIR 17 & 18			
PORT OVERALL AVERAGE	23.03	961.9	1064.1
PORT SHALLOW AVERAGE	23.31	964.9	1065.6
STBD OVERALL AVERAGE	23.03	972.4	1075.4
STBD SHALLOW AVERAGE	23.31	974.8	1076.5
AVERAGE TIMED SHIP SPEED	23.92		
CORRECTED SPEED FOR SHALLOW	24.21		

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Discussion

A. MILLWARD (University of Liverpool): The author is to be congratulated on a very interesting paper which reports a valuable piece of work. As one who is employed in research, it is appreciated that the end product of research should be applicable to real ships and it is therefore important that the results of either theoretical or experimental work should be tested against full-scale data. Unfortunately, ship owners or builders are frequently reluctant to provide that data, even though it is to their own eventual benefit, and it is very pleasing to find someone like Mr. Thew who has provided the opportunity for the full-scale trials and who also possesses the ability and experience to supervise the tests himself.

One of the major contributions to the change in the resistance of a ship in shallow water is the alteration in wave resistance. It can be seen from the theory and experimental data given in ref. 14, that the length of the ship related to the depth of water (*L/H*) appears to have the most effect on changes in resistance caused by shallow water, whereas the draught/depth ratio (*d/H*) has a much smaller effect. It was therefore perhaps a little disappointing to see most of the data in this paper quoted in terms of draught rather than static waterline length. This point is illustrated in Fig. 1 (below), which shows resistance data from tests on a planing craft model taken from ref. 16. The hull shape was that used by Keuning & Gerritsma (ref. 20) for their model 188 and was therefore basically similar to that used by the author. The data has been given as the ratio of the residual resistance in shallow water to the residual resistance in deep water at the same ship speed and has been plotted against the ship speed expressed in terms of the Froude number based on the depth of water. This form of presentation has the advantage of relating events to the critical wave speed v_c and shows that there is an increase in resistance ratio at the high sub-critical speeds, but a reduction at super-critical speeds. It can also be seen that the peaks in the added resistance occur at approximately F_{nh} = 0.9 and are very dependent on the length/depth ratio, *L/H*. No data were available for length/depth ratios of less than 3, so it is not possible to compare the model data from Fig. 1 (below) with the author's equation indicating when the shallow water effect becomes unimportant. It would therefore be very useful for future work if the author could give an opinion on what percentage increase in power on a full-size ship would be deemed to be significant due to shallow water.

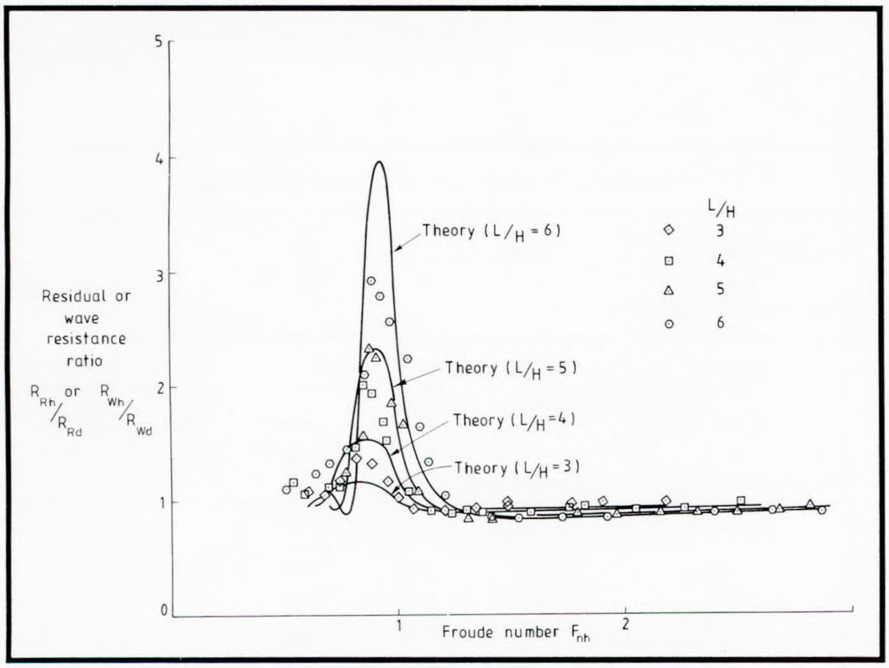

Fig. 1. The effect of shallow water on the resistance of a planing hull

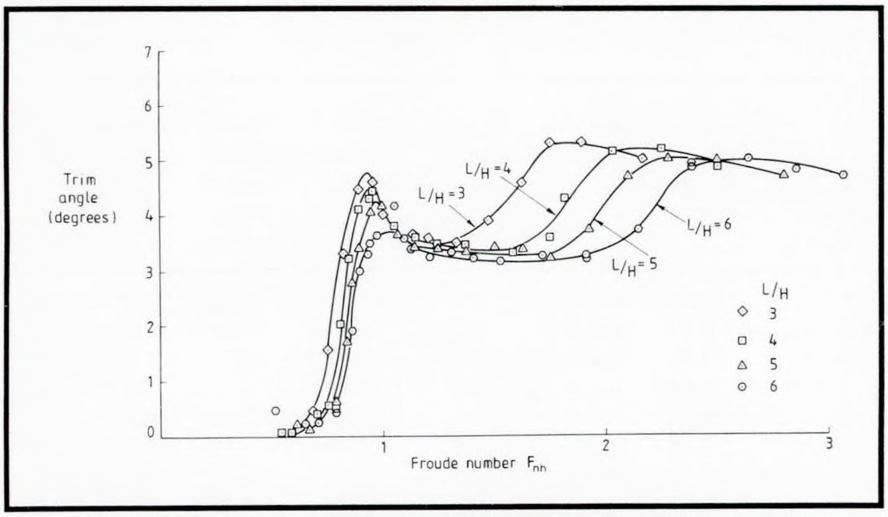

Fig. 2. The variation of trim angle with depth Froude number for a model planing hull

The author's results have shown a noticeable change in trim with shallow water near the critical speed. The corresponding data for the same model tests as before are shown in Fig. 2 (below), again plotted against the depth Froude number. As with the resistance data, there is a large change in trim corresponding to the critical wave speed (F_{nH}=1), which agrees with the author's comment that the change in trim is a good practical method of determining the critical speed. It is also interesting to see that there is a reduction in trim just above the critical speed which seems to correspond to the 'surfing' effect observed by the author. It does appear, however, that the trim changes for the model results were larger than for the full-size ship which may have been caused by the effect of the restricted width of the towing tank used in the model tests. The author's comments on this effect are noted and it is intended that research on towing tank width effects will be undertaken in the future.

The corresponding model data for the sinkage of the hull in shallow water are shown in Fig. 3 (below), and show that there is a rapidly increasing sinkage at the high

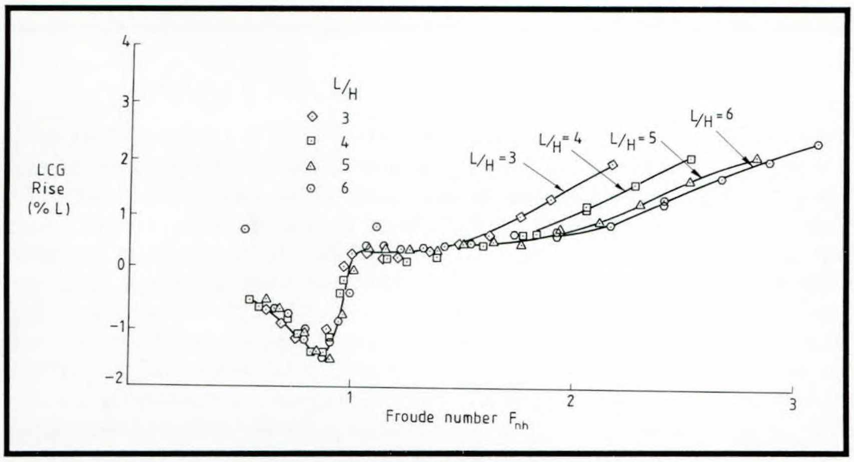

Fig. 3. The change in height of the longitudinal centre of gravity with depth Froude number for a model planing hull

sub-critical speeds but a sudden change at the critical speed. This supports the author's suggestion that reducing the sinkage with trim tabs or wedges would be beneficial since refs. 1 and 2 (below) have shown that trim tabs and wedges change both the sinkage and trim by creating added dynamic lift on the hull as well as changing the lift distribution.

The author has, however, high-lighted one of the major differences between full-scale tests and either model tests or theoretical work, that is, the presence of propeller effects in shallow water. It is clear from the author's results that this effect should not be ignored and it is hoped that suitable model work can be undertaken in the not too distant future. The author is to be congratulated on both an interesting paper and a wealth of data which will be invaluable to people working in the research field.

References

1. A. Millward, 'Effect of Wedges on the Performance Characteristics of Two Planing Hulls', *J. Ship Res.*, vol. 20, no. 4, pp. 224–232 (1976).
2. P. W. Brown, 'An Experimental and Theoretical Study of Planing Surfaces with Trim Flaps', Sevens Institute of Technology, Davidson Laboratory Report SIT-DL-71-1463 (1971).

H. D. PARSONS (Lloyd's Register of Shipping): I would like to congratulate the author and his company for the detailed full-scale results given in the paper.

Published data for full-size vessels as opposed to model results, as the author has pointed out, are rather rare. The reason for this, is that few of these fast semi-displacement craft are fitted with torsionmeters for trials.

In the 1960s, B.S.R.A. (ref. 1 below) did a lot of research into torsionmeters and thrustmeters. Their favoured type of torsionmeters was the A.E.I. meter which required a 'shell' to be clamped over the shaft. For small craft this required more space than was normally available and it was only when the electric resistance strain gauge was adapted to measure torque that power measurement for small craft became a truly practical proposition.

The accuracy of torque measurements depend on knowing the value of the modulus of rigidity of the shaft. The value for mild steel shafting according to the B.S.R.A. research did not seem to vary too greatly, but there seems to be some reservation concerning the values for stainless steel, Monel and other types of material commonly used in the shafting systems of small craft. In order to resolve these problems, small vessels were sometimes slipped, in order to allow calibration of the strain gauges by applying known torques to the shaft. Partly because of these factors, builders and owners often consider that it would be expensive to undertake fully instrumented trials on small craft.

Turning now to the question of trials analysis, Table 1 (below) shows the running free trials of a twin screw tug. The tidal current was calculated by comparing the analysis propeller speed

Table 1. Free trials of a twin-screw tug

Draughts (feet): Ford 7.33, Aft 13.75

Displacement: 390 tons

Run no.	Time at start of run	Speed over the ground (knots)	Rev./min Port	Rev./min Starboard	Power (kW) Port	Power (kW) Starboard
1	13:40	12.63	145	143	168	154
2	14:00	6.22	146	145	169	156
3	14:32	13.85	165	163	237	237
4	14:50	7.66	165	164	250	255
5	15:12	15.25	204	201	561	525
6	15:54	9.35	204	202	553	543
7	16:14	15.19	204	202	553	538
8	16:30	9.73	204	202	561	547

Run no.	Speed over the ground (knots)	Rev./min (mean)	Power (mean)	Tidal current (knots)	True speed through water (knots)	Weight (%)	Slip (%)
1	12.63	144.0	161	–3.36	9.28	10.93	5.5
2	6.22	145.5	163	3.23	9.44	10.94	4.8
3	13.85	164.0	237	–3.06	10.79	12.74	3.5
4	7.66	164.5	253	2.99	10.65	13.15	5.1
5	15.25	202.5	543	–2.98	12.28	13.19	11.1
6	9.35	203.0	548	2.84	12.19	12.42	12.0
7	15.19	203.0	546	–2.73	12.46	14.14	10.0
8	9.73	203.0	554	2.70	12.43	14.64	10.2

Average wake fraction = 12.77

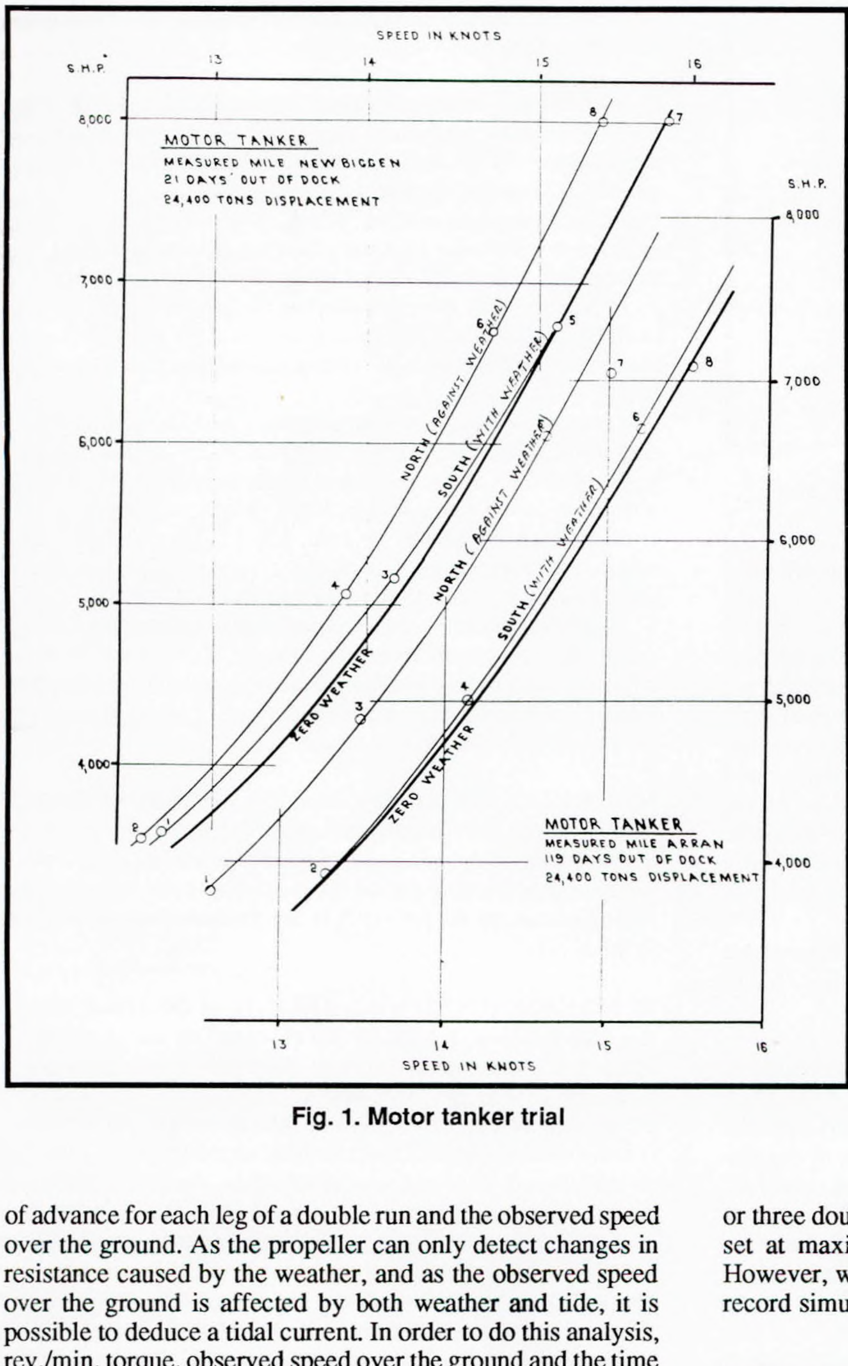

Fig. 1. Motor tanker trial

of advance for each leg of a double run and the observed speed over the ground. As the propeller can only detect changes in resistance caused by the weather, and as the observed speed over the ground is affected by both weather and tide, it is possible to deduce a tidal current. In order to do this analysis, rev./min, torque, observed speed over the ground and the time at the start of each run must be accurately know for each leg of a double run. A test of the accuracy of all the readings is that the analysis wake fractions for both legs of a double run should be similar.

The Table shows the usual trend for a displacement hull of wake fraction increasing with higher speeds and power.

Fig. 1 (above) shows the trial results of a motor tanker. The trials were analysed in the same way as the tug in the Table, all runs being corrected for tide and are speeds through the water. For these trials the ship was fitted with an anemometer and a wind direction indicator, so that the apparent wind velocity relative to the ship for each leg of the double run was known.

It is usually possible to draw 'trend lines' through the 'with weather' and 'against weather' runs. They don't normally lie on the lines as, as all yachtsmen know, the wind is rarely constant in speed and direction. If a correction is made for the wind resistance, the two curves will merge into one, generally close to the 'with weather' curve.

The point of this example is to demonstrate that if the mean power of a double run is used it has an unknown and variable weather component. Thus propulsive coefficients using tank E.H.P. (having no weather component) and the trial S.H.P. derived in the above manner are not what they seem.

I have looked in vain in the paper for a description of the weather on the trials, but I can't find any. Perhaps for the sake of completeness, the author would like to give them.

The wake fraction has a great fascination for the propeller designer. If his estimate of the value is wrong he won't get the propeller pitch right. The fact that the value increases just before the 'hump' will exercise his mind even more.

The effect of shallow water on wake fraction for 'displacement'-type hulls has been known for some time. I remember analysing the service performance of a bulk carrier trading in Northern Australia. During certain passages the ship had to squeeze through a 'hole' in a reef. The increase in the analysis wake fraction during this operation was quite dramatic. I can also remember full-scale tests being carried out by a large oil company on a 90,000 ton deadweight tanker in the Suez Canal where similar, but not so dramatic, effects were noted.

Figs. 2 and 3 (below) are graphs of wake fraction against ship's speed and weather (using apparent slip) for a container ship during two years of service. The data was abstracted from the log books.

Fig. 2. demonstrates the trend already noted in the tug trials of wake increasing with ship's speed, but does wake decrease with weather as Fig. 3. appears to show?

I would agree with the author's sentiments that the industry has itself to blame for the lack of full-scale data for semi-displacement craft. Two or three double runs on the measured mile with the tachometer set at maximum rev./min will not give much information. However, with modern electronic technology, it is possible to record simultaneously many parameters. On trial, it would be

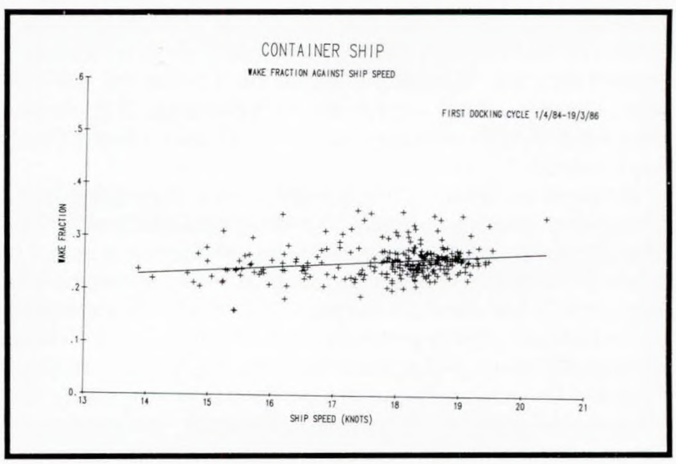

Fig. 2. Container ship wake versus speed

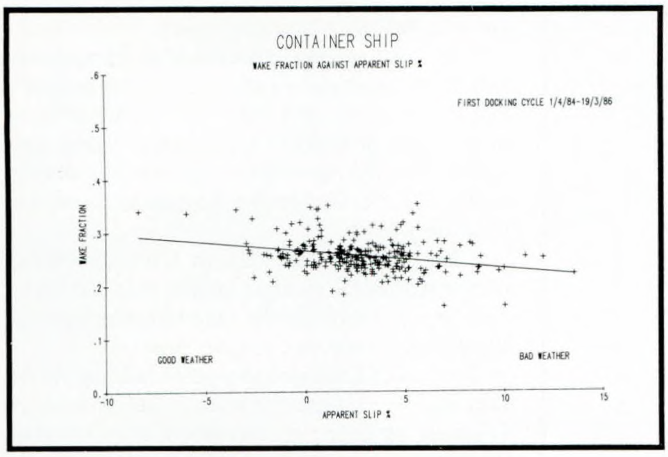

Fig. 3. Container ship wake versus apparent slip

possible by using a multichannel recorder to tape speed, rev./min and torque (both shafts), depth, rudder angle, trim, wind speed and direction, and fuel consumption, plus other engine readings. With a time base to the measurements, it is then possible to determine the variability that occurs in the readings.

If the builders and buyers could agree on a common trials requirement, it would be possible for, say, a research organization or classification society to install the equipment and analyse the results. The results of this exercise would be that the builders would get a lot of accurate data and the buyer would be happy in the knowledge that the results were recorded by a disinterested party by using a standard procedure.

Reference

1. J. Morrison, 'Recent Development in the Measurement of Propeller Shaft Torque and Thrust', *Trans. I.Mar.E. (1966) vol. 78, no. 5.*

S. E. WELFORD (R.N.L.I.): I am representing David Hudson, who was given an advanced copy of Cliff Thew's excellent paper, which was passed on to me, and I would like to make the following points. I agree 100% with the remarks of the last paragraph of the author's conclusions, namely, that more full-size data ought to be made available to the, in his words, 'research fraternity'. In reality of course, commercial discretion and time or finance, or all three, often restrict this desirable dictum.

Could we ask for a little more information from Mr. Thew please in his replies, with respect to generalized model data, to correlate with appropriate near-equivalent full-size trials data. Especially interesting would be the sinkage/heave versus speed relationship for the model. Even the briefest of full-size manoeuvring data would be enlightening, i.e. turns, Dieudonne spirals, weaves or whatever, if done, and any model manoeuvres.

Some more details of the inward- versus outward-rotating propeller rotation trials would be instructive. Did the trials crew note any difference in turning behaviour or steering response in a seaway with a different screw rotation? Our experience with the R.N.L.I. has shown a marginal (1/4 of a knot) increase in Arun lifeboat speed (top speed usually 18 knots, in the 40 boats now in this class), but a decreased response to helm in rough weather. Unfortunately, we did not have time to quantify this observation, some 8–10 years ago when the Arun was being developed.

I would also have liked to talk and ask questions about wake with respect to a tunnel lifeboat we are developing at the moment; but I think it perhaps a little too specific so I will make this point elsewhere.

D. PALMER (Marine Contract Services Ltd.): As an independent consultant who has designed many medium-speed and fast vessels over the last 25 years I would also like to congratulate Cliff Thew for his very practical paper.

In the Discussion section, which revolves around the hump speed, one extremely important factor was not mentioned, that of length/displacement ratio. One of my designs started off life as 11.5 m and was then stretched to 12.5 m, and these operate from 20–30 knots at 9–10 tons, with the longer vessel being the faster boat with less trim. Well over 900 of these have now been built.

On another design, the first vessel was 15 m and 15 knots, and the hull was subsequently stretched by 2 m, with an addition to the after end, and this second vessel achieved 17–18 knots with the identical machinery fitted. I believe length is very critical when designing approx. 1.5–2.0 speed/length ratio, where an extra metre can make a large difference to the performance for very little extra construction weight.

Regarding shallow water speed, I also remember a motor yacht sales representative who always, if possible, took the customer for a sales demonstration on a stretch of very shallow water as he said the boat log then showed 22 knots, whereas on the mile it only showed 19 knots.

M. J. BREEZE (Kort Propulsion Co. Ltd.): One of the basic parameters for the analysis is the propeller geometry. Would the author please comment on the class of manufacturing tolerance on these propellers and if all the propellers used in the various trials had exactly the same pitch and diameter values, as given in the text?

G. MACKIE (YARD Ltd.): The basis of the author's wake analysis assumes that the torque absorbed by the propeller on trials is the same as the torque absorbed in the open water propeller tests at the same advance coefficient, thus enabling the speed of advance to be derived, and hence the wake fraction. If however the characteristics of the torque curve were different in operation due to, say, cavitation when traversing the hump region, then the advance coefficient so derived would alter and so would the wake fraction. It is appreciated that it is not possible to determine J and V_a values by any other means than the open water curves on trials, but it would be interesting to view a comparison between model test results (both resistance and propulsion) for this hull form in order to assimilate the importance of the various elements that are lumped together as η_z in this paper. Has the author any plans to carry out scale model tests on this hull form?

D. BAILEY (British Maritime Technology): I write to thank the author for an interesting paper on a subject about which little is known in the way of full-scale verification of the well-documented theory on shallow water effects on ships. The programme of work carried will be a useful source of reference for designers of higher-speed vessels.

The results largely confirm the phenomena first demonstrated by Rota[12] at full scale and by Sturtzel & Graff[1] in his extensive series of model tests. Chief amongst these is the appearance of a critical speed at or near unity Froude depth number and the reduction in resistance in shallow water above this number compared with deep water. The interest and surprise in the author's paper is the apparent peak in wake values at speeds lower than might be expected. To deduce the wake values, the trials data have been worked back and the usual assumption of torque identity made.

Taking Fig. 7 as an example, where the curves relate to much the same water depth (10 m), a critical wake speed is found at 12 knots, that is at a Froude depth number of 0.62. The explanation offered later in the paper I find difficult to accept, and moreover, a single check of the data listed in Table 6 for the Junk Bay (2) results reveals the wake hump to appear at about 16 knots and not 12, i.e. at a Froude depth number of 0.86. I have only been able to use Fig. 3 and not the exact data to which this Figure refers, so that my calculations may be in slight error. In shallower water still, such as Silvermine Bay, the wake peak at approx. 12 knots is more credible since this in fact occurs at a Froude depth number of 0.91. I am therefore inclined to think that the author is reading too much into his results; abnormalities in hydrodynamic behaviour due to shallow water effects would after all be expected to occur at the same Froude depth number. And it is the Froude depth number that is important in this context, not Froude number based on length.

The authors doubts over using model experimental data for ship power predictions have little substance. Although it is true that few published data exist for the propulsive qualities of ship hulls in shallow water, this is not to say that they are not done in commercial contracts. Of course, reliable predictions can only be reached from propelled model tests, and unless there are budgetary restrictions, they are always conducted.

Finally, if I may chastise the author gently, one should not refer to shaft horse power and then give its units as kilowatts. Reference should first be made to shaft and effective power and then the chosen units stated.

Reference

1. W. Sturtzel & W. Graff, Investigation into the develop ment of optimum round-sectioned boat forms, Research report no. 137, Landes Nordrhein-Westfallen (1963).

D. K. BROWN (Royal Corp of Naval Constructors): I would like to comment on only one aspect of this most interesting paper. The effect of water depth on wake should not be unexpected since the orbital velocities of the ship-generated wave system form a major component of wake (ref. 1 below). Since the wave pattern is changed quite dramatically in shallow water it is only logical that wake changes. It is too often forgotten that the total wake of fast vessels includes potential (small), viscous and wave-making components. These last two parameters are of the same order of magnitude and of opposite sign, so that a change in one component (e.g. waves in shallow water) can cause violent fluctuations in the resultant.

Has the author any indication of the changes in thrust deduction in shallow water? It is usually supposed that thrust deduction varies with trim, and if this is so, there should be a noticeable effect.

Reference

1. A. D. K. Brown, 'Wake and Form for High Speed, Twin Screw Ships', *The Naval Architect* (October 1975).

Author's reply

Dr. Millward's comments are encouraging, particularly those which indicate that he will check some of the phenomena observed and analysed from the test described in this paper.

We can no doubt argue endlessly about presentation but my approach is solely to present data in a form that can be readily used by the practicing naval architect and marine engineer with the minimum of assumptions and search for propulsion coefficients. $©_z$, F_n, η_z, η_o, w_t, L/B and H/d_m achieve this. I accept they are not perfect in a purely theoretical sense, but then neither are the parameters, or their interaction, which go to make up the prediction of power requirements for full-scale vessels.

I further question, by implication in Fig. 12, whether the peaks of the wave-making coefficient occur close to $v\sqrt{gh}$. To deduce the wave-making coefficients, estimates have to be made of frictional and eddy-making resistance components, usually, only using the static waterline length and wetted surface area. In reality, these dramatically change as F_n increases particularly through and after the hump. Whilst I do not quarrel with the use of static waterline length (I have used the same devise), in a pure sense this varies for each speed and thus so does L/H. The latter, on a base of Froude depth number, is not then a good academic basis on which to determine the real point where the peaks of wave-making resistance occur. I appreciate that the wave-making resistance coefficient is fundamental to model/ship prediction and it is therefore of importance to be able to define its value and form. However, in comprehensive full-scale trials it is not necessary to attempt to isolate the wave-making function. So many assumptions have to be made which cannot be checked by dedicated measurement, that effectively it is possible to put the wave coefficient peaks, within reason, where you want them or 'expect' them to be. My reply to **Mr. Bailey**'s discussion is also relevant in this respect.

I should also point out that there is one other parameter not covered in model tests; air resistance of the ship structure and equipment above the main deck. Once over the hump this begins to have a measurable effect on resistance even in perfect weather.

With regard to what would be commercially acceptable for cessation of shallow water effect, I could live with the Cheung Chau results, i.e. $L/H = 1.5$.

I must also thank **Mr. Parsons** for his remarks. I agree that any shipbuilder who does not fit a torsion meter is indulging in a false economy. We fitted torsion meters at regular intervals to six out of the 18 vessels built of this class. The shafts were made of Aquamet '22'-type material which is manufactured to very close tolerances. Repeatability of results was good which gave us confidence in the modulus of rigidity quoted to us for the material. With regard to weather I mentioned in the second paragraph of the paper that the weather was good throughout. Further, all trial locations are sheltered by hills or islands except Cheung Chau.

However, I give in Table 14 (opposite) more precise details of weather and sea state.

Given good trial weather, tide and mean ship speeds may then be deduced by the expressions

$$\frac{V_{S1} - V_{S2}}{2} = V_{\text{tide}} \text{ and } \frac{V_{S1} + V_{S2}}{2} = V_S$$

where V_{S1} and V_{S2} are the each-way overground speeds at constant power. If I take runs 7 and 8 given by **Mr. Parsons** and treat them in the above manner, tide and mean speed are 2.73 and 12.46 knots respectively as opposed to 2.715 and 12.445 knots, a difference of less than 1% which is well within instrumentation accuracy limits.

I agree about dedicated trials, but analysis is something else and can be time consuming particularly when you begin to find one or two things which are 'new' or at least controversial.

We have fitted inward-turning screws to all but one of these vessels which is clearly, as **Mr. Welford** has found, more efficient. Unfortunately pre-1979 marine police crews were used to the peculiarities of outward-turning propellers and took time to adjust to the inward-turning arrangement. New crews coming through who have been brought up on inward-turning screws do not have any problems in manoeuvring. In the hazardous business of life saving, however, the rotation of propellers in my view should be decided upon on the basis of keeping the coxswain happy. He after all has to operate by skill, instinct and habit in the very dangerous environment in which lifeboat men work. A quarter knot of speed at the price of a significant change in the steering pattern could therefore make for unacceptable problems when close manoeuvring in very bad sea conditions.

On the other hand a $^1/_4$ knot in speed means arriving at the scene 'minutes' earlier which can mean the difference between life and death.

Mr. Palmer's comments do not surprise me and I believe support the thrust of my comments in connection with the 'area to avoid' in the trial conditions matrix.

In answer to **Mr. Breeze,** only two propellers were used through the trials and these are detailed in Table 1 of the paper. For the outward-turning propeller trials these were interchanged and the controls of the gearboxes were reversed. Both propellers were manufactured to I.S.O. R484 (1966) Class 1 tolerances.

Mr. Mackie's comments are of course very valid but my position is as stated in my reply to **Dr. Millward**. Open water charts are readily available to the designer in various forms published by Gawn, Troost, Radar, Burrill and others. It is then possible to link accurately measured full-scale results to this published data for use on future design. Thus in my approach, analysis W_t absorbs the effects of hull, appendages, shaft rake, sinkage and trim on a base of Froude number, whilst $©_z$ encompasses hull roughness, hull fairness, and eliminates the need for the tank propulsive coefficients. I have however lumped all the latter into one term η_z and derived this factor for use with various published resistance data (Fig. 11). As I have said earlier I accept the method is not pure in an academic sense, but it is the simplest method to derive an accurate estimation of power requirements, with the minimum of assumptions and maximum use of 'as measured' data.

With regard to cavitation through the hump we do not seem to be troubled by this although **Mr. Mackie** has a point that it could affect results, particularly in very shallow water. In that situation I would expect W_t to reduce in a similar way to the sudden reduction after it peaks at Silvermine Bay, which up to a point would be beneficial. Clearly this is another aspect to consider when carrying out a design.

Table 14. Trials weather conditions

Date	Location	Weather	Sea condition	Wind force
01-01-85	Junk Bay	Rainy/fine	Smooth	2/3
02-09-85	Silvermine Bay	Fine	Smooth	2/3
02-09-85	Adamasta Buoys	Fine	Smooth	2/3
03-09-85	Cheung Chau	Fine	Slight ground swell	2/3
03-09-85	East Lamma	Fine	Smooth	2/3

Mr. Bailey makes some interesting remarks and I trust that this full-scale data will be of use to him in his further work on the subject which I have always enjoyed following. I have to point out however that Fig. 12 clearly indicated that at only one unique point does critical speed occur at unity Froude number, there is then up to a ±15% spread either side of unity depending on actual depth where the wave of translation occurs.

I also have to disagree with **Mr. Bailey** and his use of Froude depth number in preference to Froude length number. As **Mr. Brown** shows theoretically, and **Mr. Parsons** and I show practically, wake is influenced by the ship-generated transverse wave system, at least up to the hump and it is therefore more 'correctly' related to $v/\sqrt{gL}$, not $v/\sqrt{gH}$. The peaks of wake in this paper occur in a narrow band of F_n and are clearly independent of the wave of translation or its critical speed. Logically, because of increased trim and sinkage, the magnitude of the wake peak is however affected by the wave of translation as its critical speed comes in phase with the speed of maximum wake. On this basis it is more correct to plot data on a base of Froude speed/length number on lines of constant depth/draft ratio. This also has the merit of being of more immediate use for the design of similar vessels.

I cannot find anything wrong with the data presented in Table 6 and misreading of Fig. 3 will not give a 4 knot error. Deducing K_Q on horsepower basis but using the actual kW figure for power in error will however give this order of difference, particularly if long-held views or expectations take precedence over questioning accepted theories.

In the light of the findings of this paper and the various contributions I would hope that **Mr. Bailey** takes the opportunity possibly to re-analyse the mass of data that must be available to him, and to check whether model results actually now support the findings of this paper.

I am personally not against model testing provided I know it will give me accurate results that I can use. They can moreover be very useful provided each tank has simple link factors between their model results and full-size. Rota[12], for example, probably had the benefit of, and used for reference, the results of the classic full-scale trials carried out by Rasmussen (ref. 1).

Furthermore, open water diagrams and various ship-type resistance series are invaluable since they can be linked to full-scale by w_t and η_z.

However, I maintain that wake cannot be accurately determined from pure resistance tests, and tank results can be affected by blockage (see ref. 26).

The point concerning consistency of power units is well taken and accepted.

I agree with **Mr. Brown**'s comments and his views must at least be one starting point for the theoretical approach to wake prediction. However, accurate determination of the change of orbital velocities at varying water depths will be a considerable challenge. So to will be the allowance which must be made for the effects of change of draft (Fig. 7), sinkage, finite bottom and 'surfing', as well as **Mr. Mackie**'s point concerning the effect on wake of a cavitating propeller.

I would suggest that the orbital wave theory however is unlikely to explain the change in wake between inward and outward propellers when all other parameters remain unchanged. In reality, producing an accurate theory for wake prediction that can be easily used by the industry, in my view, will be a daunting task.

We did not measure thrust due to time and cost considerations, but we will consider this on any further trial programmes.

In conclusion, may I thank all contributors for the wide-ranging remarks which I trust will have increased the value of the paper to the industry at large.