HYDRODYNAMIC TESTING OF A 3/4 SCALE AUTOSUB MODEL

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1.0 INTRODUCTION

The Autosub Project was initiated by the UK Natural Environment Research Council in 1988, in order to develop unmanned, autonomous underwater vehicles for its future marine science programmes and for global monitoring. The terms of reference of the Project, including the requirement for design, construction and operation of a Demonstrator Test Vehicle (DTV), were described in a paper presented by one of the authors at the OI '92 Conference[1].

The Outline Design Specification[2] of the DTV is prefaced by the definition of deep submergence demonstrator missions to 6000 m sea depth, from which the physical form, major subsystems and scientific payloads of the vehicle are prescribed. Furthermore, in order that the DTV should accomplish these missions, including the capability for terrain obstacle avoidance, the Outline Design Specification must, in the first place, embody knowledge of the hydrodynamic characteristics of the vehicle.

The DTV outer hull form consists of a right circular cylinder having additional fore and aft sections that are ellipsoidal and conical, respectively (Fig. 1). Following a generalised propeller study in Phase 1 of the Project[3] and the decision to use a brushless d.c. motor system, a contra-rotating propeller set was considered for installation at the vehicle aft section. Consequently, a parametric study to this effect was completed early in 1993[4]. In considering all the recommendations of this work, the option for a single propeller system was not rejected outright, however, and so a corresponding study has therefore been undertaken recently. Whatever differences may arise in the conclusions of these two studies, the question of vehicle directional stability and manoeuvring characteristics still depends largely upon the form of the body of revolution for the outer hull and the geometry, number and disposition of the control surface appendages. The decision to use aft control surfaces only was derived from the concept of the vehicle as a 'demonstrator', not only for integrated subsystem technology development, but also as a precursor to the propulsor/appendage layout of a low-drag AUV hull form, which in the light of present knowledge, precludes the use of fore-mounted hydroplanes.

In order to fulfil the DTV Outline Design Specification, therefore, it was necessary to determine the appropriate size and geometry of the control surfaces and to obtain the corresponding vehicle manoeuvring characteristics through a combination of computer simulation and hydrodynamic model testing.

This paper describes the methodology and principal features of the work carried out at the facilities of the Defence Research Agency, Haslar, to achieve the above goals.

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2.0 METHODOLOGY

A range of control surface designs were drawn up initially in relation to the DTV bare hull and the associated values of directional stability and manoeuvring indices estimated by means of a computer program[5]. Three control surface forms were selected from these designs in order to provide a range of stability margins, i.e. varying from underresponsive to overresponsive. The acceleration derivatives, or "added masses" were then computed for each control surface[6].

Despite the advances in software programming, it is still necessary to obtain data from practical experiments, in order to evaluate hydrodynamic coefficients for full six degree-of-freedom motion of submerged bodies. Furthermore, in addition to simple towing tank techniques, planar oscillatory motion and circular are trajectory model tests are also required. Planar Motion Mechanism (PMM) and Rotating Arm (RA) tests were therefore conducted with a geometrically similar, instrumented model of the DTV hull, using in turn the three selected control surface configurations so that empirical values of manoeuvring derivatives and coefficients could be determined. Since the tests were conducted, for convenience, with a model of reduced scale in fresh water, the data are presented in the customary non-dimensional form, see Appendix.

The manoeuvring characteristics of the DTV (having three different appendages, in turn) were evaluated by using the acquired empirical data in a six degree-of-freedom trajectory simulation computer program[7]. The results were then assessed in order to recommend a final control surface configuration for the Autosub DTV Outline Design.

3.0 PROCEDURE

3.1 Selection of 3 Candidate Appendage Designs

The physical data required to begin the design and to carry out the later computer simulations were obtained from an earlier edition (Issue D, December 1991) of reference 1. The principal features of the DTV hull were those indicated in Fig. 1, with the exception of the illustrated control surfaces, which are only symbolic at this stage. The form and submerged displacements of the hull are approximately 3600 kg and 2780 kg respectively, in sea water based on a density of the latter of 1025 kg m^{-3}.

The sign convention adopted for the DTV body motion and hydroplane deflection is shown in Fig. 2. It differs from standard submarine convention because all four hydroplanes (i.e. control surface flaps and rudders) will be independently controllable. The approach taken here is: looking along the shaft of the control surface, outwards from the body, a positive deflection is clockwise. Thus, to create a turn to port, the upper rudder must be set to a negative angle and the lower rudder to a positive angle.

During the subsequent experiments it was possible to record the position of only one of the pair of deflected hydroplanes. This was either the upper rudder or the starboard sternplane (flap), depending upon the orientation of the model on its longitudinal axis during the tests. The graphs produced from those experiments

involving control surface deflections, name a single appendage on the abscissa, but the force or moment recorded on the ordinate is that produced by the deflected pair.

A range of several candidate specifications for the control surfaces were chosen and processed through the computer program SUBSIM[5] in order to obtain the basic vertical and horizontal stability margins G_v and G_h, respectively. A dynamical system is said to be stable when, in the free motion following a disturbance, the effect of that disturbance ultimately becomes vanishingly small. G_v and G_h are derived using the coefficients of the equations which represent the dynamics of a submerged vehicle. Consequently, it may be shown that,

$$G_v = 1 - \frac{M_{uw}\,(m + Z_{uq})}{Z_{uw}\,M_{uq}} \qquad \text{where} \quad M_{uw} = \frac{\partial^2 M}{\partial u \partial w}$$

$$M_{uq} = \frac{\partial^2 M}{\partial u \partial q}$$

$$m = \text{mass}$$

$$Z_{uq} = \frac{\partial^2 Z}{\partial u \partial q}$$

A positive value of G_v indicates stability. Also, a similar expression may be derived for G_h, but because of the symmetrical design of the DTV hull, G_h will have the same value as G_v.

Three different appendage designs were then selected from the range of candidate specifications for manufacture. They were named A, B and C, with Appendage Set A being the smallest and Appendage Set C the largest (Fig. 3). The calculated values of G_v (and G_h) were 0.375 (over responsive), 0.669 and 0.865 (under responsive) for A, B and C respectively. All three designs have the trailing edge 0.7 m forward of the DTV aft end and the stock a further 0.186 m forward, where the hull diameter is approximately half the maximum diameter of 0.9 m. All the appendage designs are NACA0015 aerofoils.

3.2 Model Manufacture

Although the tests were to be conducted with a fully submerged body for which dynamic similarity requires only the equality of Reynolds number between the model and the DTV, it is still desirable in this case to manufacture the former to a scale that is as near full size as possible. The restriction on this desirability, however, was the limiting capability of the force transducers to be used inside the model. The Glass Reinforced Plastic model hull was, consequently, built to a scale of $1/1.346$, i.e. 0.74 x full scale. The overall length of the model was 5.2 m and a baseplate was fitted at the centre in order to mount the necessary instrumentation and to provide an attachment for the "swords". The latter were used to connect the model to a carriage on either the PMM (on the towing tank carriage) or the R.A. A motorbox fitted at the rear of the model drove the propeller and it also contained the stepper-motors for setting the control surface angles. All the motors were controlled remotely from the model. Owing to the symmetrical arrangement of the four control surfaces, only one opposite pair needed to be driven by the servo motors. These could represent rudders or hydroplanes, depending upon the application. Furthermore, these two driven control surfaces operated independently and they could therefore provide roll control.

The appendages were manufactured from an epoxy based resin, CIBATOOL and they were bolted individually onto the hull.

The model was fitted with an existing DRA propeller having a diameter of 0.427 m. The propeller boss size was increased to 190.9 mm at the forward end and 181.4 mm at the aft end in order to match the tapered hull diameter. Although a contra-rotating propeller set was not available for the tests, it was considered that the single propeller which had been chosen would,nevertheless, provide a useful aft body flow simulation. Fig. 4 shows divers ballasting the model prior to testing in the No. 2 Towing Tank at DRA Haslar.

3.3 Experimental Facilities

Two separate sets of experiments were to be carried out at DRA Haslar facilities: all three appendage sets were to be tested in No. 2 Towing Tank which incorporates a Planar Motion Mechanism; sets B and C were to be tested using the Rotating Arm in the Manoeuvring Tank. In addition, these experiments fall into two categories, namely steady state and dynamic.

In the steady state experiments, particular fixed conditions were applied, e.g. body angles and fixed control surface deflections. These include all the RA tests and those PMM experiments for which the oscillator mechanism was not used.

The dynamic experiments are those conducted on the PMM using the oscillator mechanism to produce motion in the vertical plane, whilst the model is being towed at a constant forward velocity.

The model was ballasted for neutral buoyancy and with zero BG, prior to being mounted on each facility.

3.4 Scale Effects

In order to maintain the same Reynolds number as the DTV and thus preserve the nature of the flow round the experimental body, it is necessary to run the model at a speed that is inversely proportional to the scale of the model. (In cases where this is not physically possible turbulence stimulator pins and wires may be fitted near the front of the hull and any appendages). Owing to the large scale of the model ($1/1.346$), however, turbulence stimulators were not required for these experiments.

Since the proposed operating speed of the Autosub DTV is 2 ms^{-1}, the model was therefore required to be towed at a speed of 2 x 1.346 = 2.69 ms^{-1}. All experiments were performed using this model speed.

4.0 EXPERIMENTAL PROGRAMME

4.1 Rotating Arm

A series of tests was carried out for both Appendage Sets B and C. The model was suspended by a single horizontal "sword" suspended below a carriage. The carriage was situated on rails and it could be locked into place at any position along the radius of the rotating arm. A schematic arrangement of the model (shown

sectioned), suspension system and carriage, viewed radially along the Rotating Arm, is illustrated in Fig. 5. The model was placed on the RA at radii, which varied from 13 m to 26 m.

The model was fitted with a six component balance for measuring forces in the X, Y and Z directions both fore and aft, about the centre of buoyancy. All experiments required one 360° revolution of the arm, the steady state data being gathered in the furthermost 90° arc from the starting position, i.e. 135° to accelerate and decelerate. The propeller was driven at the self-propulsion rotational speed. This rotational speed of the propeller had been previously determined in the Towing Tank and it was to be used for all subsequent tests. The propeller motor was switched on at the commencement of each RA test, as the model left its starting position.

A waiting time of 10 to 15 minutes was required between tests in order to allow the water to settle.

The first set of tests involved varying the drift angle β of the model by turning it through a specified number of degrees about a vertical line passing through the mass centre. This is equivalent to applying a fixed sideslip velocity v', where

$$v' = -\sin \beta$$

A zero drift angle signifies that the body is always tangential to the circle it is describing.

In the second set of tests, a zero drift angle was maintained while the upper and lower rudders of the model were set at fixed positions. (A few additional tests were conducted with the model having differential rudder angles, i.e. roll moments were produced).

The range of angles applied varied with radius of turn. Three different radii (13 m, 17.33 m and 26 m) were used for the first set of tests, with two intermediate radii for zero drift and rudder angles. The length of radius determined the rate of turn since the model speed was maintained at 2.69 ms^{-1}. The ranges of rate-of-turn, drift angle and rudder angle were chosen to represent the conditions that were thought most likely to occur during routine operation of the DTV.

4.2 Planar Motion Mechanism

The model was suspended from the PMM by two "swords", one fore and one aft. The sword spacing was equi-distant about the centre of buoyancy of the submerged model. Each sword was connected to an electric motor driven eccentric mechanism in order that sinusoidal motion could be transmitted, to the model, in the vertical plane. The swords operated independently; the phase between them being adjustable.

The PMM was attached to a carriage that was mounted on rails (Fig. 6). The carriage was accelerated to a uniform speed of 2.69 ms^{-1} during each test, before data was acquired. For steady state tests, during which the PMM was maintained in a fixed configuration, data was gathered over a 10 second period. During the dynamic tests, however, data was recorded over 3 complete cycles of the PMM.

The instrument sensors installed within the model consisted of six block gauges used for measuring forces in the three orthogonal axes fore and aft, a roll accelerometer and a tilt box which contained inclinometers to record pitch and roll angles.

The following series of tests were conducted with each of the appendage sets:

4.2.1 Self-propulsion

This was to determine the propeller rotational speed required to drive the model at the same speed as the carriage towing it, i.e. when a zero net force is measured in the x-direction. The required propeller speed was approximately 258 rev./min for each appendage.

In addition, an unpropelled run was carried out in order to gain an assessment of the overall model drag. The model was towed at 2.69 ms^{-1} with the propeller motor switched off. The propeller was, however, free to "autorotate" and it did so at approximately 100 rev./min.

4.2.2 Steady State Pitch:

The model was towed with a fixed pitch angle and the corresponding forces measured. This test is equivalent to applying a uniform vertical velocity component w, so that:

$$w' = \sin\theta = \frac{w}{U}$$

The range of angles applied was from -10° to +10° in steps of 2°.

4.2.3 Steady State Sternplane Angles

During these tests the model was maintained horizontal, while the sternplane angles were varied in order to measure the corresponding depth forces and pitch and roll moments. The maximum applied stern angle was 25°.

4.2.4 Dynamic Heave

The model was again maintained horizontal for these tests, but with the PMM swords moving in phase. The amplitude of the model vertical oscillatory motion was 25.4 mm while the frequency was varied incrementally between 1.35 and 4.3 $rads^{-1}$.

4.2.5 Dynamic Pitch

During these tests the phase between the PMM swords was adjusted to produce pure pitching motion, i.e. rotation only in the vertical plane about the mass centre of the model.

4.2.6 Dynamic Roll

For these tests, the model was constrained to oscillate about its longitudinal axis by means of an arm attachment parallel to the aft sword. The roll amplitude remained fixed at 2.4° while the frequencies were the same as those identified in Section 4.2.4.

4.2.7 Second Moment of Mass

This series of tests was carried out for Appendage Set B only, since the magnitude of I_y, the second moment of mass about the y-axis, was unlikely to differ significantly between appendage tests. The carriage was stationary, with the water filled model suspended from the PMM in air in the dry dock. The phase between the swords was adjusted for pure pitching motion and the tests performed at the frequencies identified in Section 4.2.4.

5.0 PRESENTATION OF DATA AND RESULTS

5.1 Rotating Arm and Steady State PMM

Owing to the hull symmetry of the Autosub DTV, it was only necessary to conduct the model tests either in the horizontal or vertical plane. The Rotating Arm tests were performed in the horizontal plane. The independent variables recorded for each run were: drift angle or rudder angle; radius of turn and angular velocity of the Arm. The dependent variables recorded were the X, Y and Z forces and the M, N and K moments. The Z force and M moment were not considered in the results, however, since the cross-coupling terms were of no significance for the DTV design.

Although the PMM tests were carried out in the vertical plane, the results of some of the steady state runs were "rotated" into the horizontal plane in order that they should be combined with the corresponding RA results. Where the zeros of the lines of best fit from each facility did not match up the results were shifted slightly so that there was a better agreement. For these combined RA and PMM results, the independent variables, non-dimensional sideslip velocity and rate of turn could be calculated and corresponding graphs plotted. Curves were fitted to the plots using a computer program which applied a statistical least squares method. It is not possible to show all the plots in this publication although two graphs, applicable to Appendage Set B, are namely:

Y' against V' for the different values of R', and

Y' against δr for the different values of R',

where Y' is non-dimensional force in the y direction
V' is non-dimensional velocity in the y direction
δr is rudder angle
R' is model length divided by Arm radius (non-dimensional rate of turn).

These graphs, showing the test results with lines of best fit are shown in Fig. 7 and Fig. 8, respectively.

5.2 Dynamic PMM

During the dynamic tests, the discrete sampling of the signals was determined by optical encoder clocking pulses. Although several channels were recorded, time skew between sampling the first and last channel was negligible. Data was sampled at a rate of 256 per PMM cycle, over 3 complete cycles.

The dynamic tests reproduced some results that were also obtainable by the steady state PMM and RA experiments. These are Z_w', Z_q', M_w' and M_q'. They are, however, derived in a different way. In the steady state tests, particular fixed conditions were applied and the actual hydrodynamic forces on the model, measured; this could be termed a direct method. The technique using the dynamic PMM is an indirect procedure, because having measured the hydrodynamic forces on the model for a specific forced motion, it is assumed that these forces satisfy certain equations. These equations are then solved to obtain values of the hydrodynamic derivatives. The equations of motion which were used are:-

$$(m - Z_{\underline{w}})\,\underline{w} - Z_{\underline{q}}\,\underline{q} - Z_{uw}\,uw - (m + Z_{uq})\,uq = Z(t)$$

$$(I_y - M_{\underline{q}})\,\underline{q} - M_{\underline{w}}\,\underline{w} - M_{uw}uw - M_{uq}uq + mg\,\overline{BG} = M(t)$$

where Z(t) and M(t) represent the forced motion. These equations are a subset of the full equations of motion for a deeply submerged vehicle. (In addition, the use of the PMM oscillator is the only way of obtaining the acceleration derivatives, or added masses).

5.3 Estimates of Body Drag

During the self-propulsion experiments for each Appendage set, one run was carried out with the propeller switched off. However, the towing of the model caused the propeller to rotate freely. The X force, or drag, measured from this run is shown in Table 3. This is the closest available estimate of body drag, but it does include the drag of the 'auto-rotating' propeller.

5.4 Simulation of Manoeuvres

Using the coefficients derived from the test results, full trajectory simulations were undertaken using the computer program SUBSEA[7]. Owing to limited space, only some of the data used for this is included; see Tables 1 and 3. Also incorporated in the simulations was the concept of sliding mass within the DTV, which had the effect of moving the centre of vehicle mass up to either 21 mm fore or aft. Since the recommended value of BG was 20 mm, the maximum pitch angle that could be produced by using the sliding mass alone, was approximately 45°, which is the desired maximum angle for either descent or ascent of the DTV.

The following simulated manoeuvres are considered here:

(a) Depth stability
(b) Circle manoeuvres
(c) Steady dives

(Limitation of space in this publication precludes reference to depth overshoot and extreme rise, although all of these manoeuvres were reported in Reference 8).

5.4.1 Depth Stability

Using the derivatives obtained from the dynamic PMM experiments, the stability margins, Gv, for the three designs are:

Gv(A) = 0.398 Gv(B) = 0.705 Gv(C) = 0.939

so they are clearly all stable. The value of the damping ratio could also be calculated but it is best demonstrated by observing the behaviour following a disturbance.

5.4.1.1 Control Surfaces

The disturbance in this case was provided by 10 seconds of application of sternplane angle. Four runs were carried out for each appendage. Table 2 shows the magnitudes of depth and pitch achieved at the end of 10 seconds application of control surface (hydroplane) angles corresponding to 5, 10, 15 and 20 degrees. The maximum values of pitch angle achieved following the 10 second disturbance is also shown in Table 2. In addition, time history plots of pitch and depth, corresponding to a control surface angle of 10°, are shown in Fig. 9. It can be seen that with reference to pitch decay, A is underdamped, B has good response without overshoot and C is heavily damped. The damping ratios calculated from the derivatives are 0.54, 0.88 and 1 for Appendage sets A, B and C respectively.

5.4.2 Circle Manoeuvres

Turns were simulated with reference to rudder angles of 5°, 10°, 15°, 20° and 25°. At the start of each simulated run, the DTV rudders were "moved" to a fixed angle which was then maintained for the duration of the manoeuvre. The characteristics of each turn that had been computed were:

(a) Drift Angle, β — The angle between the heading and the direction of travel.

(b) Rate of Turn — Non-dimensional i.e. rate of turn x model length _ U.

(c) Advance — The distance travelled in the direction of the original course from the time the rudder is put over.

(d) Tactical Diameter — The distance moved at right angles to the original course.

(e) Snap Roll — The peak roll angle reached during the initial stages of the turn, before returning to a steady roll angle, which was about 2° for all runs.

(f) Speed Loss — The initial speed was 2 m/s. The figure computed is the percentage speed loss after one complete turn.

Fig. 10 shows a plan view of the circle manoeuvre, at 25° rudder angle, for all three appendage sets.

5.4.3 Steady Dives (fixed control surface angles)

The DTV mission requirements[2] specify a maximum desired angle of descent of 45°. To maintain this, a small control surface angle will be required to oppose the restoring moment produced by BG. To oppose the lift force produced by the control surface, the body adopts an angle of attack and thus the pitch angle will be greater than 45°. Simulations were carried out to determine the required control surface angle, simply by applying fixed angles and observing the descent angle produced. An initial speed of 2 m/s was used. The values of particular interest were: required sternplane angle, pitch angle, angle of attack, the drag produced by the control surfaces and the angle of attack, and the steady speed.

Note that the drag produced by the angle of attack, the body drag, is negative, i.e. reducing the required thrust. This is because the direction of travel is not the same as the direction of thrust, and some of the overall drag is acting to oppose the lift force from the control surface and therefore is not opposing the thrust of the propeller. The forces and moments which act on the DTV in this instance are summarised illustratively in Fig. 11.

6.0 CONCLUSIONS

The method of hydrodynamic testing of a 3/4 scale model of the Autosub Demonstrator Test Vehicle (DTV), using the Planar Motion Mechanism and Rotating Arm facilities at DRA Haslar, has been described in this paper.

Details of three candidate control surface designs have been given in Fig. 3 and a selection of the results, including hydrodynamic coefficients, presented in Tables 1 to 4.

The full trajectory computer simulations and manoeuvring characteristics for the DTV, fitted in turn with each appendage set, were reported in Reference 8. Selected depth and manoeuvring characteristics have been illustrated in this paper, see Figs. 7 to 10.

The purpose of the original work[8] was to recommend an appropriate control surface design for the DTV. The recommendation, based upon an analysis of the simulated manoeuvers referred to above, indicated that Appendage Set B was the most appropriate of the three control surface designs. Appendage Set B has a faster response to hydroplane and rudder deflections than Set C, but it is not prone to "overshoot" as exhibited by Set A. In the horizontal plane Appendage Set B is more manoeuvrable than Set C although it does not exhibit as large a speed loss as Set A.

In addition to the work described in this paper, the effects of BG variation on the Autosub DTV performance are reported in Reference 9.

The hydrodynamic test programme described in this paper is a contribution to the fulfilment of the Outline Design Specification for the 1200 km range, 6000 m depth capability Autosub Demonstrator Test Vehicle.

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Description	Value
Length	7 m
Form Displacement	3600 kg
Water Density, ρ	1025 kgm^{-3}
I_x	320 kgm^2
I_y, I_z	8304 kgm^2
X_g, X_b	0.34 m
Z_g (nominal)	0.02 m
Hydroplane Limit	25°
Hydroplane Rate	10°/s

(The nominal values identified with the Autosub DTV are assumed to be approximately the same (if not identical) for each appendage set).

(Tables 1 and 4 list the values which, for the most part, have been derived either theoretically or experimentally for use in the DRA Haslar submerged body simulation program SUBSEA).

Table 1

Appendage A

Plane Angle (deg)	5	10	15	20
Depth at 10 s (m)	5.2	6.1	6.8	7.3
Pitch at 10 s (deg)	14.0	25.5	34.8	42.3
Max. Pitch (deg)	17.9	31.6	42.7	51.9

Appendage B

Plane Angle (deg)	5	10	15	20
Depth at 10 s (m)	4.9	5.7	6.4	6.8
Pitch at 10 s (deg)	9.5	18.5	26.9	34.4
Max. Pitch (deg)	10.8	21.3	31.4	41.0

Appendage C

Plane Angle (deg)	5	10	15	20
Depth at 10 s (m)	5.0	5.8	6.5	6.9
Pitch at 10 s (deg)	9.4	18.1	25.9	32.7

Max. Pitch (deg)	10.3	20.0	29.9	37.6

Table 2. Depth Stabilities of Appendages A, B and C.

Appendage Set	Model Drag (N)	Full Scale Drag (N)
A	124.1	127.5
B	129.0	132.6
C	137.8	141.6

Table 3. Comparison of Body Drag with relation to Appendages A, B and C.

Coefficient	Set A	Set B	Set C
$Z_{\underline{w}}'$	-16.69	-17.39	-17.17
$Z_{\underline{q}}'$	-0.1738	-0.1691	-0.2469
Z_w'	-26.078	-29.134	-36.631
Z_q'	-8.73	-11.221	-13.95
$Z_{\delta s}'$ (p,s)	±5.089	±5.309	±7.080
$M_{\underline{w}}'$	-0.1738	-0.1691	-0.2469
$M_{\underline{q}}'$	-0.9918	-0.9801	-1.030
M_w'	6.001	4.677	2.11
M_q'	-4.495	-5.043	-6.17
$M_{\delta s}'$ (p,s)	±2.081	±2.208	±2.914
$Y_{\underline{v}}'$	-16.69	-17.39	-17.17
$Y_{\underline{r}}'$	0.1738	0.1691	0.2469
Y_v'	-26.078	-29.134	-36.631
Y_r'	8.73	11.221	13.95
Y_p'	-0.1798	-0.2130	-0.2567
$Y_{\delta r}'$ (l,u)	±5.089	±5.309	±7.080
$N_{\underline{v}}'$	0.1738	0.1691	0.2469
$N_{\underline{r}}'$	-0.9918	-0.9801	-1.030
N_v'	-6.001	-4.677	-2.11
N_r'	-4.495	-5.043	-6.17
N_p'	-0.0249	-0.0103	0.00706
$N_{\delta r}'$ (l,u)	2.081	2.208	2.914
$K_{\underline{p}}'$	-0.00132	-0.00152	-0.00262
K_v'	-0.1557	-0.1742	-0.1988
K_r'	0.05423	0.06216	0.07278
K_p'	-0.0418	-0.0533	-0.0656
K_δ'	-0.1467	-0.1876	-0.2655

(These non-dimensional coefficients form the best linear fit around the origin. All values are x 1000). (p, s _ port, starboard; l, u _ lower, upper).

Table 4. List of Coefficients Linearised over Small Range.

NOTATION

Below is a list of symbols which appear in the text, along with a brief description. Most terms are explained where they are introduced.

m	Mass
l or L	Length
BG	Distance between centre of buoyancy and centre of gravity
ρ	Water density
I_x, I_y, I_z	Moments of inertia
X, Y, Z	Forces in the x, y, z directions
K, M, N	Moments in a clockwise direction about x, y, z axes respectively
U	Speed
u, v, w	Linear velocities in x, y, z directions respectively
p, q, r	Angular velocities about x, y, z axes respectively
$\underline{u}$, $\underline{v}$, $\underline{w}$	Linear accelerations in x, y, z directions respectively
$\underline{p}$, $\underline{q}$, $\underline{r}$	Angular accelerations about x, y, z axes respectively
δ, δsp, δrl, etc. or ds, dr etc.	Control surface deflections (letters refer to specific location: 1st sternplane, rudder; 2nd port, starboard, upper, lower)
Z_w, Y_r, N_p etc. or Z_{uq} etc.	Hydrodynamic derivatives e.g. $Z_w = \left.\frac{\delta Z}{\delta w}\right\vert_{w=0}$
$Z_{\delta s}$, $K_{\delta r}$ etc.	Forces and moments from sternplanes and rudders
G_v, G_h	Stability margins in vertical and horizontal planes
α	Angle of attack, vertical plane
β	Drift angle, horizontal plane
ω	PMM frequency
prime, e.g. X'	Indicates non-dimensional term

NOTATION (contd)

Hydrodynamic Coefficients or Derivatives

The forces in the equations of motion can be broken up into orthogonal components, for example:

$$Y = vY_v + pY_p + rY_r + \underline{v}Y_{\underline{v}}, + \underline{p}Y_{\underline{p}}, + \underline{r}Y_{\underline{r}}, + Y(t)$$

where Yv, Yr etc. are the hydrodynamic coefficients or derivatives and Y(t) is the contribution to the force which is a result of some externally applied disturbance.

It is also assumed that the derivatives Y_v, Y_p, Y_r are directly proportional to forward speed, u, so they may be written as Y_{uv} etc. where

$$Y_{uv} = \frac{\partial^2 Y}{\partial u \partial w}$$

However, when only concerned with a single speed, it is sometimes convenient to drop the u subscript, but its existence should still be inferred.

Likewise, for example, the term $Z_{uu\delta s}$ is sometimes abbreviated to just $Z_{\delta s}$.

APPENDIX

Non-dimensionalising the Equations of Motion

The non-dimensionalising of the equations of motion is largely a matter of convenience, although at one time it was thought that suitable non-dimensionalising parameters might lead to the possibility of directly comparing derivative values for submerged bodies of different size and shape. There have been various methods used in attempts to achieve this aim, and the following has been adopted here.

It is convenient to non-dimensionalise with respect to U^2, since the forces and moments depend upon the square of forward speed. This factor alone ensures that the coefficients of the non-dimensional equations are not speed dependent. It is also found that derivative values for different size submerged bodies are of the same order if the length is used as a parameter. Forces are thus divided by $\frac{1}{2}\rho U^2L^2$ and moments by $\frac{1}{2}\rho U^2L^3$. The velocity components are divided by U and the angular velocity components by U/L. For example:

$$w' = \frac{w}{U} \qquad q' = \frac{qL}{U} \qquad m' = \frac{m}{\frac{1}{2}\rho L^3} \qquad I_y' = \frac{I_y}{\frac{1}{2}\rho L^5}$$

$$Z_w' = \frac{Z_{uw}}{\frac{1}{2}\rho L^2} \qquad Z_{\underline{w}}' = \frac{Z_{\underline{w}}}{\frac{1}{2}\rho L^3} \qquad M_w' = \frac{M_{uw}}{\frac{1}{2}\rho L^3} \qquad M_{\underline{w}}' = \frac{M_{\underline{w}}}{\frac{1}{2}\rho L^4}$$

$$Z_q' = \frac{Z_{uq}}{\frac{1}{2}\rho L^3} \qquad Z_{\underline{q}}' = \frac{Z_{\underline{q}}}{\frac{1}{2}\rho L^4} \qquad M_q' = \frac{M_{uq}}{\frac{1}{2}\rho L^4} \qquad M_{\underline{q}}' = \frac{M_{\underline{q}}}{\frac{1}{2}\rho L^5}$$

$$K_p' = \frac{K_{up}}{\frac{1}{2}\rho L^4} \qquad Z_\delta' = \frac{Z_{uu\delta}}{\frac{1}{2}\rho L^2} \qquad M_\delta' = \frac{M_{uu\delta}}{\frac{1}{2}\rho L^3} \qquad K_\delta' = \frac{K_{uu\delta}}{\frac{1}{2}\rho L^3}$$

So, for example,

$$Y' = \underline{v}'\, Y_{\underline{v}}' + \underline{r}'\, Y_{\underline{r}}' + v'\, Y_v' + r'\, Y_r' + \delta\, Y_\delta' + p\, Y_p' + \underline{p}\, Y_{\underline{p}}'$$

is fully dimensionalised in the following way:

$$Y = \tfrac{1}{2}\rho L^3\, \underline{v}\, Y_{\underline{v}}' + \tfrac{1}{2}\rho L^4\, \underline{r}\, Y_{\underline{r}}' + \tfrac{1}{2}\rho L^2\, Uv\, Y_v' + \tfrac{1}{2}\rho L^3\, Ur\, Y_r' + \tfrac{1}{2}\rho L^2\, U^2\, \delta Y_\delta'$$

$$+ \tfrac{1}{2}\rho L^2\, Up\, Y_p' + \tfrac{1}{2}\rho L^3\, \underline{p}\, Y_{\underline{p}}'$$