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COMMENTS AND NOTES
ON THE
LATERAL CONTROL OF
SWATH AND OHF SHIPS

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Introduction

This paper will look at the lateral plane control aspects of SWATH type ships with particular emphasis on the Tri-hull versions like the O'Neill Hull Form (OHF) concept. This paper complements the work done on the longitudinal plane control aspects of SWATH ships of reference 1.

In order to assess the effects of basic physical parameters of SWATH ships on the lateral stability and control characteristics, one must have a method of calculating the four basic lateral plane derivatives which determine a ships lateral stability and maneuverability. Two radically different approaches, one empirical, one analytical, for predicting the lateral plane derivatives were assessed as to their applicability to Tri-hull SWATHs such as the OHF. Since neither of these approaches in their present form were really applicable, new expressions to predict the lateral characteristics are developed. The lateral plane derivatives calculated from these expressions match the available test data for eight different SWATH ships with an accuracy more than sufficient for this task.

These newly developed expressions are then used to assess the effects of change in geometric parameters and different rudder configurations on the maneuverability of SWATH type ships. Based on these assessments, the paper closes with a list of conclusions and recommendations.

Development of the Expressions for Lateral Derivatives of SWATH Ships

In this section, expressions with which to predict the non-dimensional lateral derivatives, Y'_v , N'_v , Y'_r and N'_r from the basic geometry of a SWATH are developed. Before getting into the development, let us first look at two reported approaches, one analytical and one empirical for predicting the lateral derivatives of SWATH ships.

The analytical approach of Hirano and Fukushima (ref. 2) applies the low aspect ratio wing theory developed by Bollay (ref. 3). In the development of their equations, however, Hirano and Fukushima completely neglect the lower hull and assume that only the wetted portions of the strut contribute to the lateral forces and moments. This is an assumption which becomes questionable if the lower hull is large and the wetted strut depth is small. They state in their paper that the span of the strut is assumed to be twice its actual depth in calculating the aspect ratio because the free surface was considered as a fixed boundary (low Froude number). In fact in their paper only for those models with a lower hull was the span of strut made twice its depth in calculating its aspect ratio. In the cases where there were no lower hulls the actual depth was used. It is as if they assumed the lower hulls acted as an end plate rather than the free surface. The excellent agreement (with the exception of N'_v) between prediction and test results shown in the paper is so impressive that it warrants a closer study. With some minor modification (the definition of Aspect Ratio for instance) or an imperical adjustment, this analytical approach would be an excellent prediction tool, applicable to both single and twin strut SWATH ships and the OHF.

This approach was not used in this paper because of the above mentioned inconsistency and the discrepancy in N'_v. In addition programming these equations for solution was beyond the scope of this task.

Lacking a verified analytical technique, an empirical approach, i.e. curve fitting to test data, can be used. If the empirical approach is going to be used to extrapolate to quite different configurations, the form of the equations and the geometric ship parameters used should follow basic principles. An empirical approach reported by Waters and Buchinski (ref. 4) was a curve fitting technique of the test data for four different strut and rudder versions of the SWATH 6. For the parameters used in their paper, the test values of N'_v becomes more negative as the center of the strut area is moved aft. This is a direct contradiction of basic physics and therefore either the form of the equations or the choice of the geometric parameters is poor. For this reason the prediction techniques of reference 4 were not felt adequate for this task.

In this paper the approach will be to set up the form of the expressions so that the derivatives vary with the geometric parameters as dictated by basic physics and then to determine the constants empirically from test data. To eliminate the effect of the free surface distortion, which occurs at higher Froude numbers, all test data used to determine the empirical constants were taken from tests at a Froude number (based on lower hull length) less than 0.2 (10 Knots for the SWATH 6 series). This limitation was imposed for the following reasons.

(a) The surface distortion at higher Froude numbers is so highly dependent on the lower hull shape, that it is hard to find simple general expressions for the lateral derivatives at Froude numbers where surface distortion becomes significant.

(b) Test data available is from fully captive models run on a rotating arm. At higher Froude numbers, the tests do not accurately model the full scale ship which would be free to heave and trim* and have lateral derivatives radically different than a fully captive model.

With this background let us proceed to the development of the expressions for the lateral derivatives, Y'_v , N'_v , Y'_r and N'_r.

Y'_v , Lateral Force/Sway Velocity

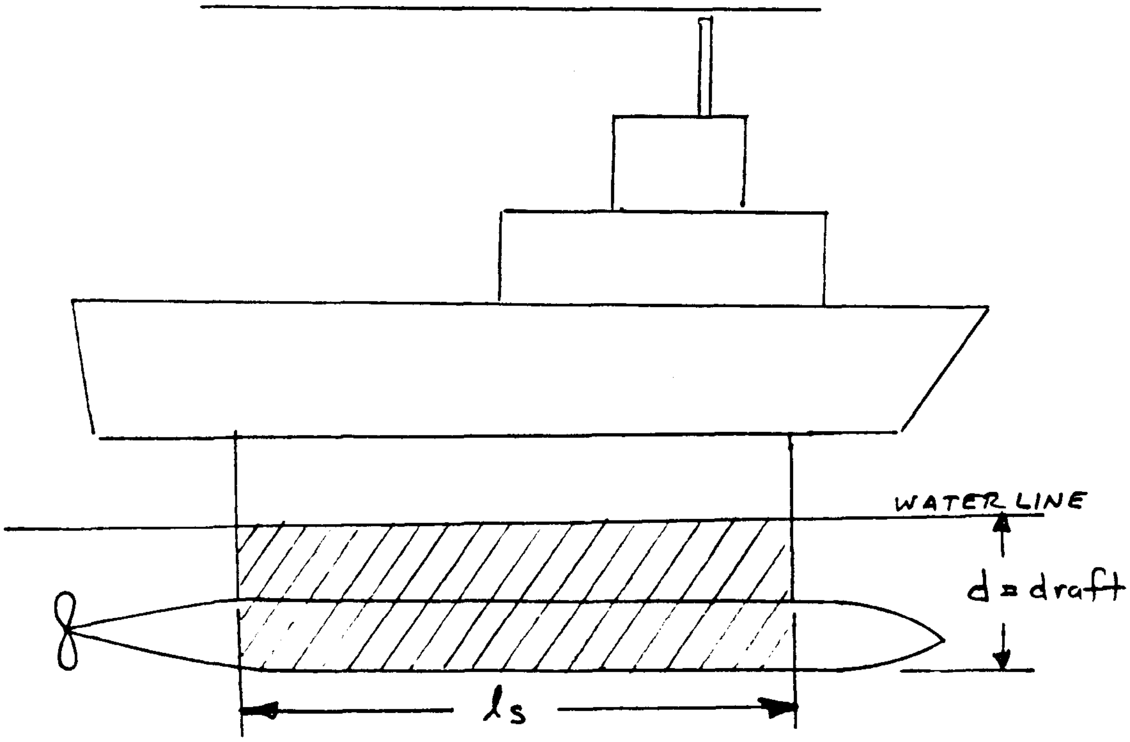

Figure 1. Side view of SWATH

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* It is assumed that if the ship had active pitch control, variations in trim would be minimal.

A side view of a SWATH is shown above in figure 1. In the lateral plane, the simplest representation is a wing with a span equal to the draft, d, and a chord equal to the strut length, l_s, as represented by the crosshatched area.

The protruding nose and tail sections of the lower hull are assumed to contribute very little to the lateral force due to sway velocity.

The aspect ratio, AR, of this wing which equals d/l_s is very low and in accordance with Jones (ref. 5) its lift curve slope varies with aspect ratio. The angle of attack due to side force is v/U or v'

The lateral force, Y, therefore is

$$Y = - C_{L_\alpha} v' \quad (\tfrac{1}{2}\rho U^2) \; l_s d$$

$$Y'_v = \frac{\partial Y'}{\partial v'} = - C_{L_\alpha} \; (d/l_s) = - C_{L_\alpha} \; (AR)$$

Since C_{L_α} is proportional to the aspect ratio Y'_v is proportional to the aspect ratio squared. Figure 2 shows Y'_v as measured in the SWATH 6 series test plotted against the square of their respective aspect ratio.

Since the best straight line that can be drawn through these test data does not pass through the origin, it takes more than a simple constant of proportionality to represent this curve.

Two different representations fit the data well

one $Y'_v = - 8.133[(AR)^2 - .004]$ (1)

or $Y'_v = - 10(AR)^2 + .05(AR)$ (2)

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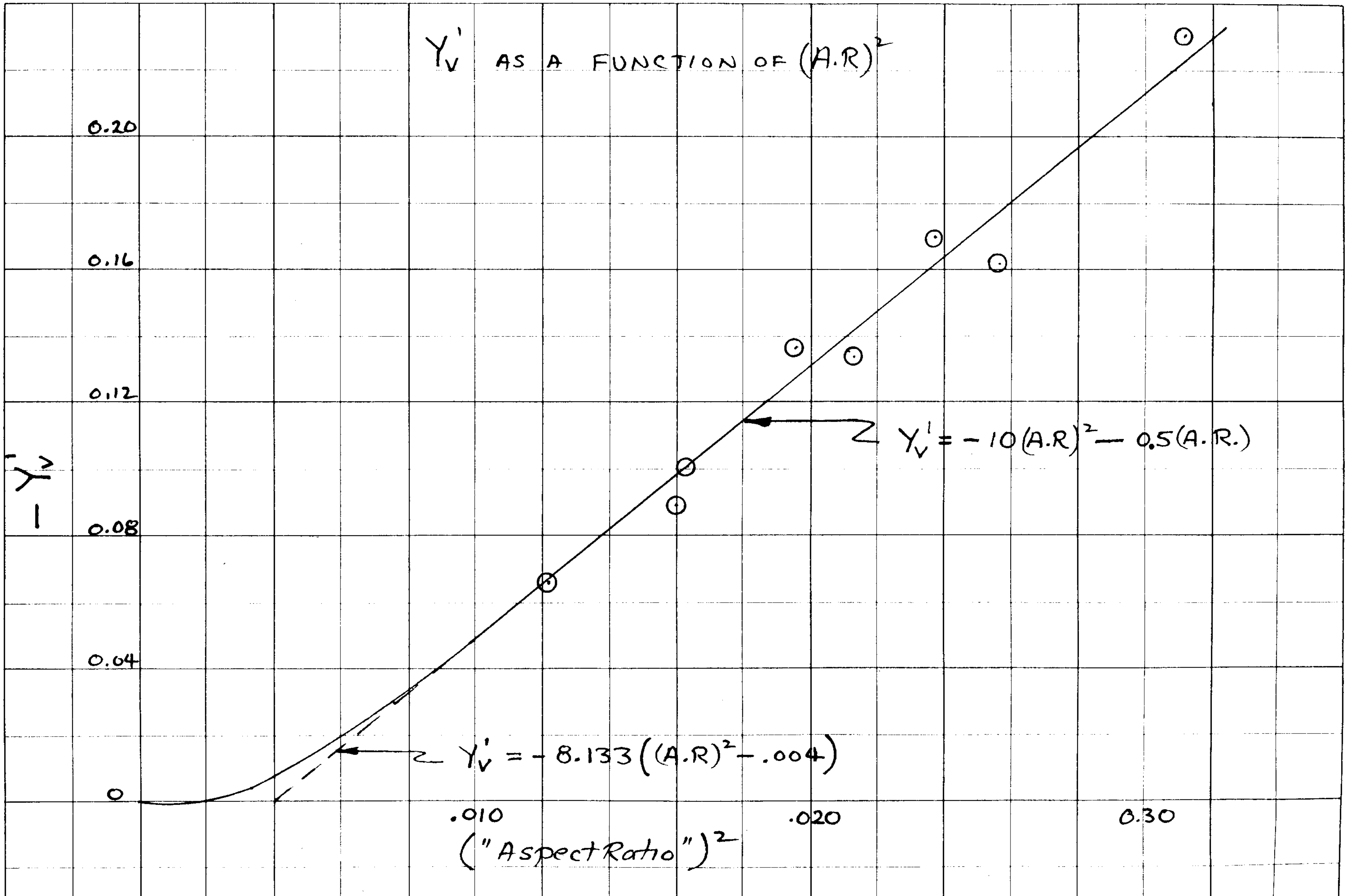


FIGURE 2

The latter was used as it goes to zero as the draft goes to zero. Neither expression, however, should be considered valid for aspect ratios above 0.5 based on figure 3 which shows the lift curve slope, C_{L_α}, obtained from these expressions and from the classical expression for C_{L_α}.

N'_v , yaw moment/sway velocity

For any lifting surface there is a point at which the lifting force can be assumed to act which also results in the proper moment about the reference point. The yaw moment due to sway velocity then is simply the product of the lateral force due to sway velocity and the longitudinal distance from the reference point to where this force may be assumed to act. The reference point in this paper will be the center of gravity. Applying this we get,

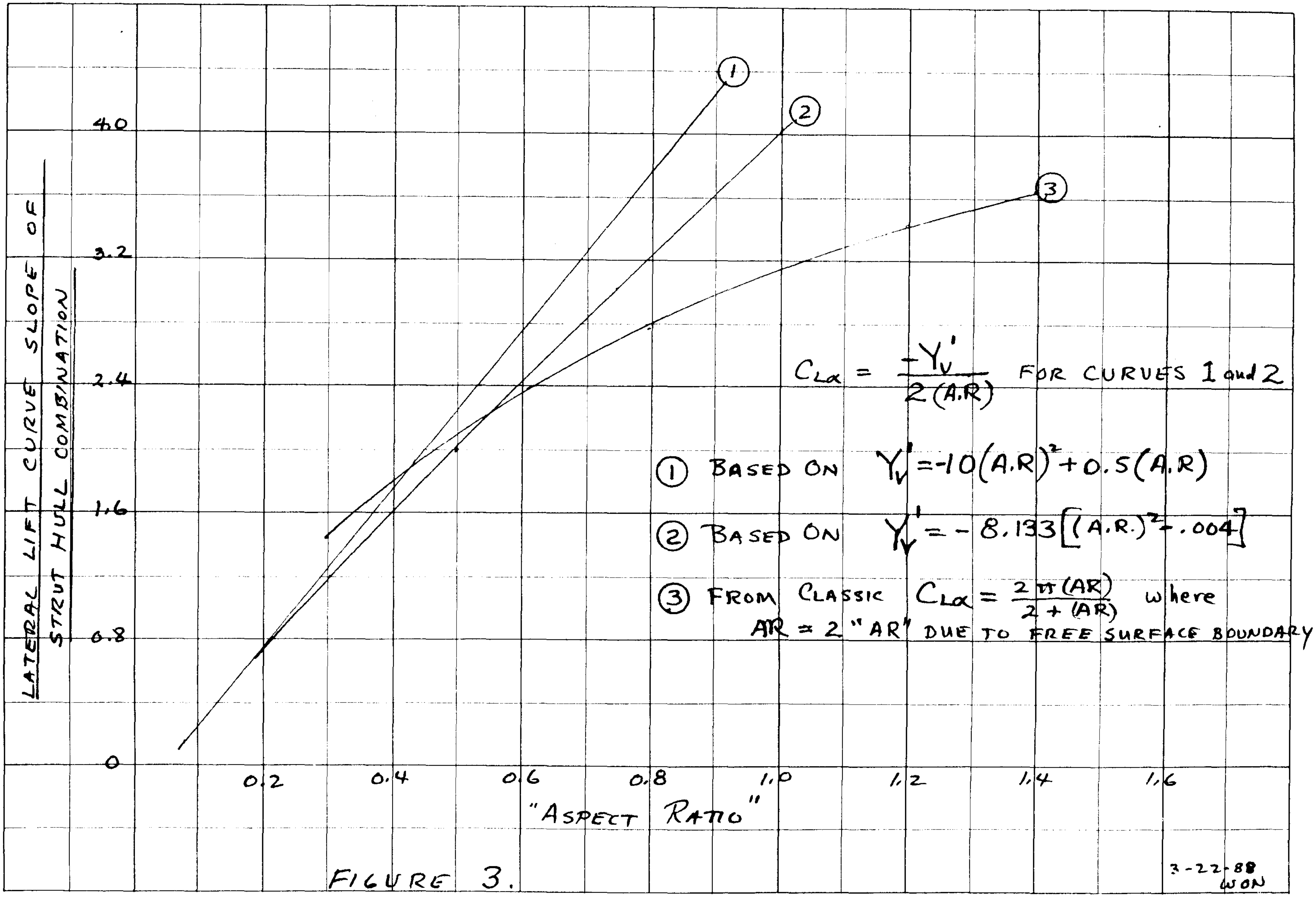
$$N'_v = Y'_v(X'_{cs} + k) \qquad (3)$$

where X'_{cs} is defined as the longitudinal distance from the center of gravity to the center of the strut divided by the strut length. X'_{cs} is positive when the center of the strut is forward of the center of gravity. From the results of the SWATH 6 series tests at 10 knots, the average value of k is 0.554. Therefore,

$$N'_v = Y'_v\ (0.554 + X'_{cs}) \qquad (4)$$

Y'_r , lateral force/yaw moment

The center of gravity for all SWATH 6 series ships is near the center of the strut and the derivative of the lateral force with yaw rate, Y'_r , is positive. It is obvious, if the center of


LATERAL LIFT CURVE SLOPE OF
STRUT HULL COMBINATION
4.0
3.2
2.4
1.6
0.8
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
"ASPECT RATIO"
1
2
3
$C_{L\alpha} = \frac{-Y_v'}{2(A.R)}$ FOR CURVES 1 and 2
(1) BASED ON $Y_v' = -10(A.R)^2 + 0.5(A.R)$
(2) BASED ON $Y_v' = -8.133[(A.R.)^2 - .004]$
(3) FROM CLASSIC $C_{L\alpha} = \frac{2\pi(AR)}{2+(AR)}$ where
AR = 2 "AR" DUE TO FREE SURFACE BOUNDARY
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WON

FIGURE 3.

gravity, the point about which yaw is measured, is moved far enough aft that Y'_r must become negative. The form of the equation for Y'_r must show Y'_r decreasing as X_{cs}' increases and eventually going from positive to negative. Assuming that Y'_r also varies directly with Y'_v the simplest form of the expression for Y'_r is

$$Y'_r = A\ Y'_v\ (1 - BX_{cs}') \tag{5}$$

The values of the constants A and B which give a good fit to the SWATH 6 series test data were determined to be A=-0.392 and B=4.0, thus

$$N'_r = -\ 0.392\ Y'_v\ (1 - 4X_{cs}') \tag{6}$$

N'_r, yaw moment/yaw rate

Figure 4 below shows a horizontal cross-section of a SWATH strut in which the center of gravity is X_{cs} from the center of the strut.

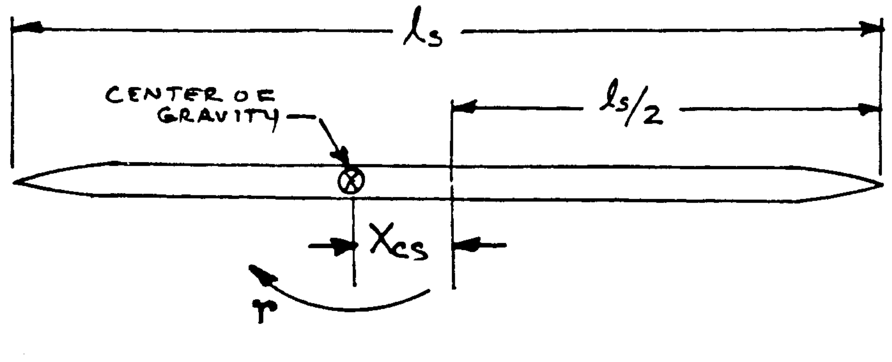


Figure 4. Cross-section of strut

Looking at the segment of the strut either side of the center of gravity the following relationships are obvious.

(a) The wetted area is proportional to the length of that side.

(b) The average flow velocity perpendicular to strut due to yaw rate is proportional to the length of that side.

(c) The effective moment arm of the force created by the yaw rate is proportional to the length of that side.

The contribution of each of the two segments of the strut to the yaw moment due to rate, N'_r, is proportional to the cube of the length of each segment respectively. Adding the contribution from each side, we get

$$N'_r = K[(0.5 + X'_{cs})^3 + (0.5 - X'_{cs})^3]$$
$$= 0.25K[1 + 12(X'_{cs})^2] \qquad (7)$$

To determine 0.25K, $N'_r/[1 + 12(X'_{cs})_2]$ as measured in the SWATH 6 series test is plotted against "aspect ratio" in figure 5. The straight line shown in figure 5 which is a plot of 0.27 (AR - .05) was chosen as a reasonable fit to the data.

$$N'_r = 0.27(AR - .05)[1+ 12\ (X'_{cs})^2] \qquad (8)$$

and since $Y'_v/10AR = (AR - .05)$

$$N'_r = \frac{.027}{AR} Y'_v[1 + 12(X'_{cs})^2] \qquad (9)$$

It should be noted that strut length is used to non-dimensionalize the derivatives. For those configurations where there is a rudder close to the trailing edge of the strut as in the SWATH 6AS and the SWATH 6E, the effective strut length used is the sum of the strut length and rudder chord.

The comparisons of the calculated derivatives to the test results of the SWATH 6 series are shown in Table 1. These comparisons are also shown graphically in Appendix A. In addition a comparison of predictions to test results for the T-AGOS 19 and the models of Hirano and Fukushima (ref. 2) are included in Appendix A. The predictions for the models of Hirano and Fukushima are drawn on figures taken directly from reference 2. The effective strut length and X_{cs}' were scaled from their sketches as they were not given in the paper.

All these comparisons show that the expressions derived in this paper are sufficiently accurate for trending studies of effect of geometric changes on the stability and maneuverability of SWATH type ships.

SHIP		STRUT LENGTH	"ASPECT RATIO"	X'_{cs}	Y'_v	N'_v	Y'_r	N'_r	M'	C
6A	Cal	172.2	.1545	.014	-.1614	-.0916	.0597	-.0287	.03898	.0065
Design	T				-.1709	-.0899	.065	-.0355		.0084
6A	Cal		.1766		-.2235	-.1270	.0827	-.0342	.04053	.0130
Deep	T				-.2331	-.1083	.0758	-.0355		.0121
6B	Cal	280	.1279	0	-.0996	-.0552	.0390	-.0210	.02212	.00302
Design	T				-.1005	-.0624	.0383	-.0207		.00309
6B	Cal		.1462		-.1406	-.0779	.551	-.0260	.02300	.00616
Deep	T				-.1349	-.0780	.584	-.0204		.00551
6AS	Cal	189.2	.1406	-.032	-.1274	-.0665	.0562	-.0247	.02939	.00493
Design	T				-.1384	-.0626	.0612	-.0251		.00546
6AS	Cal		.1606		-.1776	-.0927	.0785	-.0302	.03055	.00981
Deep	T				-.1608	-.098	.0694	-.0310		.00879
6E	Cal	240.3	.1107	-.0551	-.0672	-.0335	.0322	-.0169	.01435	.00173
Design	T				-.0678	-.0339	.0339	-.0177		.00186
6E	Cal		.1265		-.0967	-.0482	.0463	-.0213	.01492	.00357
Deep	T				-.0897	-.0478	.0425	-.0209		.00319

Cal - Calculated using expressions developed in this paper.

T - Test results from references 4 and 6 adjusted by non-dimensionalizing to strut length.

M' = Non-dimensional mass.

C = Stability Index = $Y'_v N'_r - N'_v(Y'_r - M')$
Must be positive for stability.

TABLE 1. Calculated and Measured Values of Lateral Derivatives for the SWATH 6 Series at Design and Deep Draft.

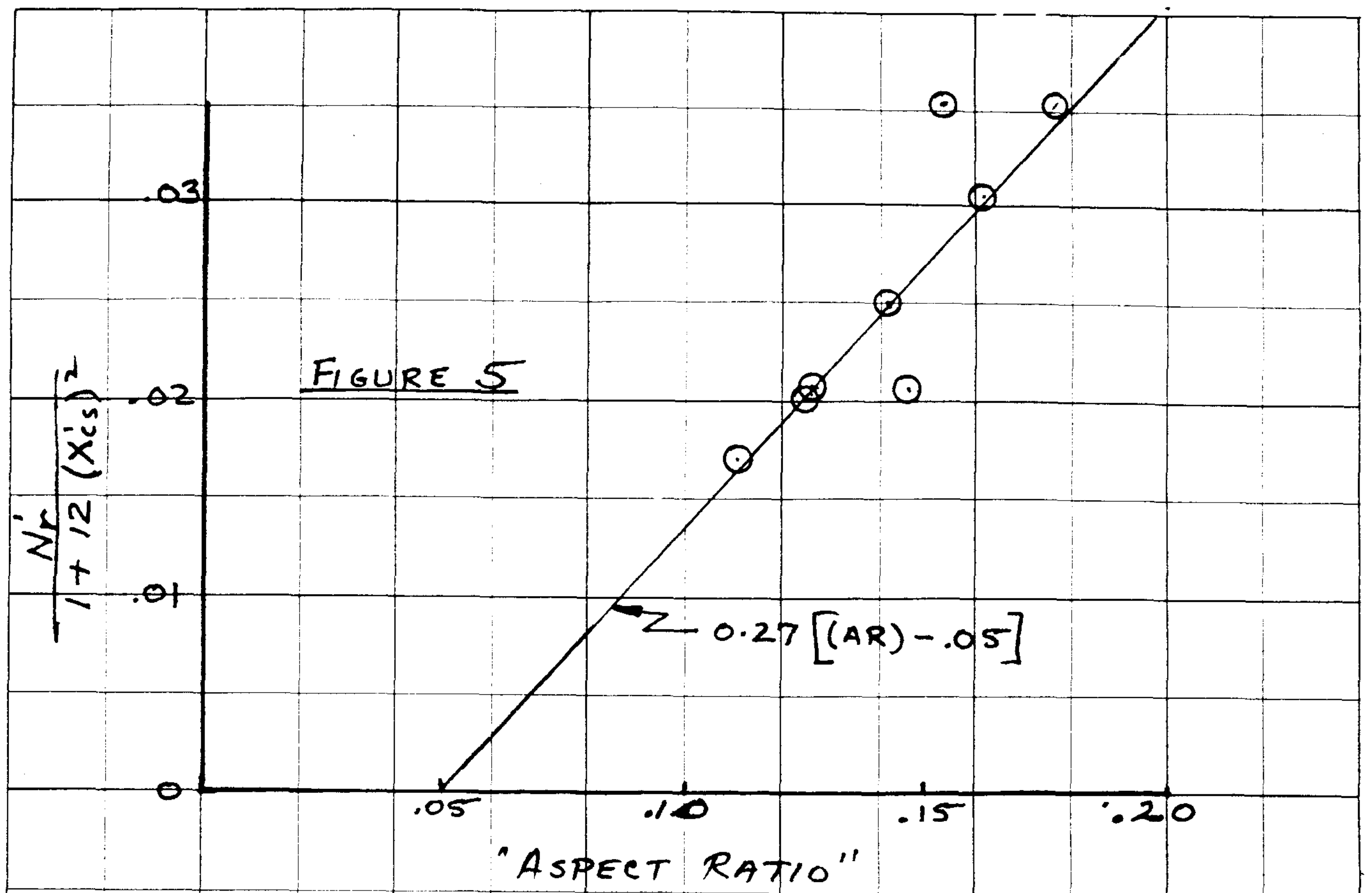
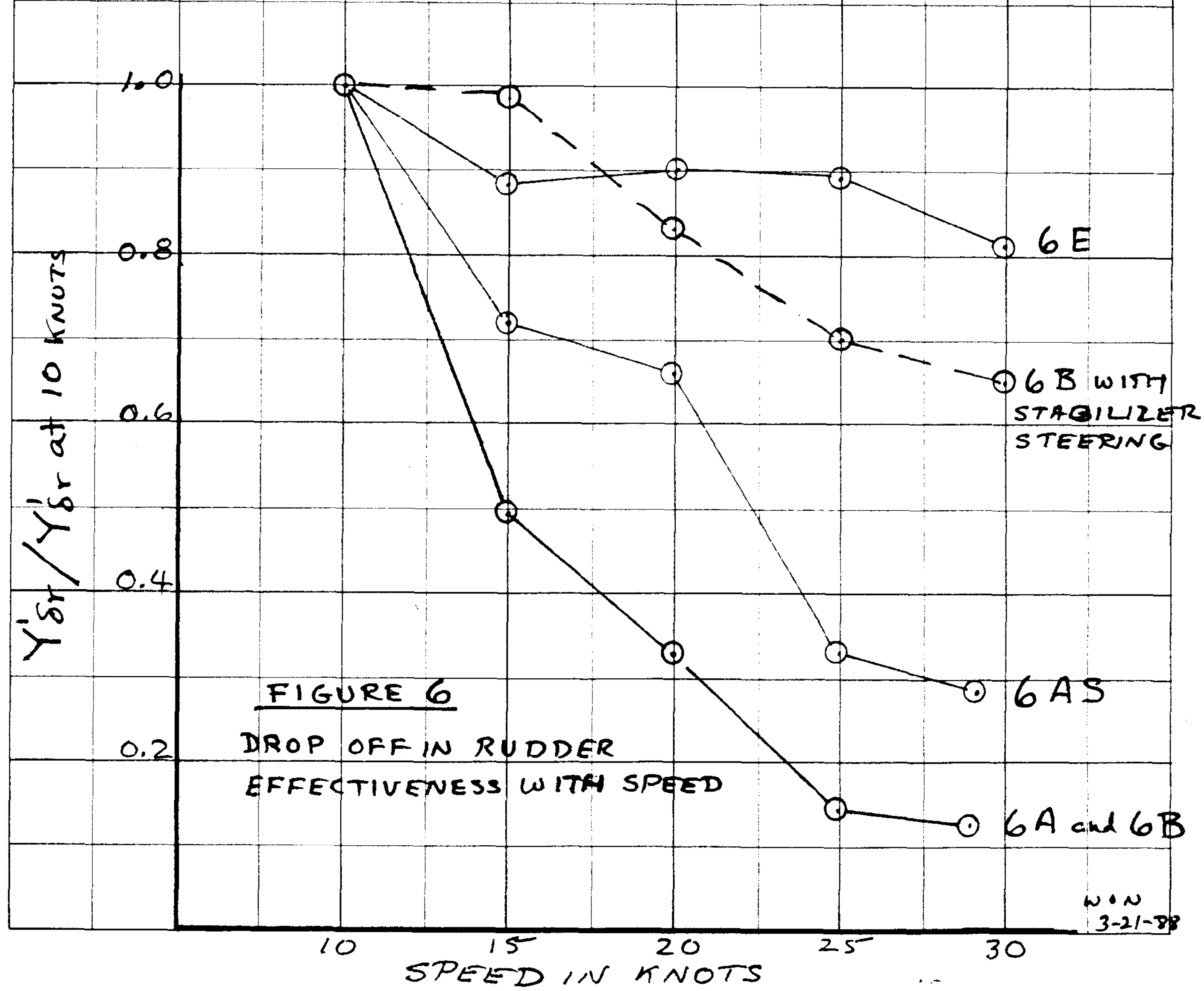


FIGURE 5
$\frac{N_r'}{1 + 12\,(X_{cs}')^2}$
.03
.02
.01
0
0.27 [(AR) - .05]
.05
.10
.15
.20
"ASPECT RATIO"


$Y'_{\delta r} / Y'_{\delta r}$ at 10 KNOTS
1.0
0.8
0.6
0.4
0.2
6E
6B WITH STABILIZER STEERING
6AS
6A and 6B
FIGURE 6
DROP OFF IN RUDDER EFFECTIVENESS WITH SPEED
WON
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10
15
20
25
30
SPEED IN KNOTS

Effect of Geometry on Lateral Characteristics of SWATHs

In this section, the expressions derived in the preceding section will be applied to conventional and OHF type SWATH ships. To do this with conventional SWATHs, we will substitute these expressions for their respective derivatives into the equation for $\delta_r{}^R/_L$ below

$$\delta_r{}^R/_L = \frac{Y_v' N_r' - N_v'(Y_r' - m')}{Y_v' N_{\delta r}' - N_v Y_{\delta r}'} \tag{10}$$

Putting in the expressions for Y_v', N_v', Y_r', and N_r' in the equation (10) we get

$$\delta_r\ R/L = \frac{a(AR)^2 + b(AR) + c + m'd}{N_{\delta r}' - d\,Y_{\delta r}'} \tag{11}$$

Where $a = 15.68(X_{cs}')^2 + 4.766\ X_{cs}' - 2.172$

$b = -\ 4.024(X_{cs}')^2 - 0.238\ X_{cs}' - -.1614$

$c = .162(X_{cs}')^2 + .0135$

$d = X_{cs}' + .554$

Equation (11) can be used to assess the effect of altering X_{cs}' and aspect ratio on conventional SWATH ships. For sea keeping considerations the distance between the center of gravity and the center of flotation of a SWATH should be less than 6% of the ship's length. Since the center of the strut closely tracks the center of flotation the variation in X_{cs}' is restricted to 6% or plus and minus .06.

Using the SWATH 6B for which $X_{cs}' = 0$ as a base line, we can apply equation (11) to see the effects of varying X_{cs}'. If we make the reasonable assumption that the rudder moment arm is 40%

of the length of the ship, that is, $N'_{\delta r} = 0.4\ (l_h/l_s)\ Y'_{\delta r}$ (where $N'_{\delta r}$ and $Y'_{\delta r}$ are based on strut length) we find that the turn radius, R, decreases 23% for $X'_{cs} = .06$ and increases 22% for $X'_{cs} = -\ .06$ over that of the baseline ($X'_{cs} = 0$).

To check the effects of changes in the "aspect ratio" we will assume that the draft of the ship stays the same, therefore the strut length must be changed to vary the aspect ratio. In conventional SWATH ships, the practical range of strut length is assumed to lie between 67% and 100% of the lower hull length. If we again use the SWATH 6B as a baseline (strut length/hull length = 0.867) and maintain $X'_{cs} = 0$ by keeping the center of the strut at the center of gravity, we find that the turn diameter for a strut length equal to the hull length is 24% greater than that of the baseline and 21% less for a strut length 67% of the hull length for the same rudder force and moment.

One can conclude from the above that the center of the strut to center of gravity distance and the strut length to hull length ratio have a significant effect on the turn radius for same rudder force and moment. Their effect is not so large as to take precedence over primary considerations such as sea keeping, GML and wetted area. Strut shaping can alter X'_{cs} to a certain extent beyond the limits imposed by LCB, LCF spacing.

To use the equations for the lateral derivatives for a tri-hull or OHF type SWATH, one must apply them to the component parts based on their respective strut length, normalize the non-dimensional lateral derivatives to a common length (usually the center hull length) and sum of the components. Table 2 shows how this is done on an OHF model built by the David Taylor Research Center, and for the same model with the outboard hulls moved forward 50 feet (full scale) relative to the center hull. The key full-scale dimensions of these two OHFs are given in Table 3.

	Based on local strut length				Based on center hull length				Stability Index "C"
OHF As Built	Y'_v	N'_v	Y'_r	N'_r	Y'_v	N'_v	Y'_r	N'_r	
Center Hull *	-.0343	-.0212	.0101	-.0087	-.0160	-.00675	.00320	-.00189	
Outer Hulls	-.0387	-.0162	.0234	-.0139	-.0119	-.00275	.00398	-.00131	
	Ship Total				-.0279	-.0095	.00718	-.0032	.0000919
OHF With Outer Hull Moved 50 Feet Forward									
Center Hull *	-.0343	-.0180	.0149	-.00839	-.0160	-.00573	.00476	-.00183	
Outer Hulls	-.0387	-.0227	.0131	-.0115	-.0119	-.00386	.00224	-.00109	
	Ship Total				-.0279	-.00959	.00700	-.00292	.0000824

* Equation for Y'_v is based on two hulls. OHF has single hull, therefore values obtained from equation must be halved.

TABLE 2. OHF Derivatives and Stability Indices

	Model as Built	Model with Outer Hulls 50' Forward	OHF with Overhanging Rudder Similar to 6E OH AFT	OH FWD
<u>CENTER HULL</u>				
Length	324.92 ft.	324.92 ft.	300.00	300.00
Diameter	16.25	16.25	17.00	17.00
Draft	24.75	24.75	25.50	25.50
Strut length	221.88	221.88	235.00*	235.00*
Strut Setback	51.52	51.52	51.52	51.52
C.G. station	176.44	156.08	170.27	149.91
"Aspect Ratio"	0.1115	0.1115	0.1085	0.1085
X_{cs}'	0.063	-0.0288	0.0053	-0.0813
<u>OUTER HULLS</u>				
Length	232.50	232.50	232.50	232.50
Diameters	11.58	11.58	11.58	11.58
Draft	16.58	16.58	16.58	16.58
Strut length	180.00	180.00	180.00	180.00
Strut setback	111.00	60.00	111.00	60.00
"Aspect Ratio"	0.0921	0.0921	0.0921	0.0921
X_{cs}'	-0.1364	0.0338	-0.171	0
<u>Displacement</u>				
Center hull	1730 tons	1730 tons	1730	1730
Strut	325	325	325	325
Outer hull	967	967	967	967
Outer strut	367	367	367	367
Total	3389 tons	3389 tons	3389	3389
M'(l = 324.92)	.0069	.0069	.0069	.0069
<u>Rudder</u>	None	None	SWATH 6E Type	SWATH 6E Type
Chord	---	---	13.12	13.12
Span	---	---	18.00	18.00
Y (l = 324.92)	---	---	.00546	.00546
N (l = 324.92)	---	---	-.00243	-.00278

* Includes 13.12 foot chord rudder.

TABLE 3. Characteristics of OHF and Variants

Not surprisingly, the OHF with the outboard hulls moved forward has a lower index of stability. One would suspect with so large a shift forward in the lateral area, a much larger decrease than 10%. With this forward shift in lateral area, however, there is a concomitant forward shift in the location of the center of gravity.

The stability index, c, forms the numerator of the linear expression, equation (10), for the turning radius of a ship and thus the lower the stability index the smaller the turn radius. The rudder force and moment form the denominator of equation (10), and it is to these that we now turn our attention. Four basic rudder schemes have been tried on SWATH ships. They are:

(a) Trailing edge strut rudder

The SWATH 6A and 6B have trailing edge flaps on their struts which act as rudders to create the necessary side force and turning moment.

(b) Rudder on top of lower hull, aft of strut

The SWATH 6AS aft of its strut has a spade rudder on top of the lower hull of sufficient span to pierce the free surface.

(c) Overhung rudder aft of propeller

The stern of the SWATH 6E upper hull, which extends well aft of the lower hull, has a spade rudder hung from it just aft of the propeller.

(d) <u>Stabilizers aft on the inboard sides of the lower hulls</u>

The T-AGOS-19 has large stabilizers mounted at a 20 degree dihedral, inboard and well aft on the lower hulls. The side force required for turning consists of the horizontal component of lift on these differentially deflected stabilizers plus the concomitant pressure forces on the lower hull and adjacent strut. The relative magnitude of these forces are quantified by Waters and Hickok (ref. 6) based on model tests on a SWATH 6B, modified for stabilizer steering.

Those rudders which are near or pierce the free surface lose effectiveness rapidly at Froude numbers (based on lower hull length) above 0.2 (10 Knots on the SWATH 6 series) because of their unwetting due to the depression of the free surface. This is clearly demonstrated in figure 6 (page 13), which clearly shows that those surfaces which remain fully wetted exhibit much less sensitivity to speed.

Regardless of which rudder scheme is selected, conventional SWATH ships exhibit such a high degree of directional stability, that they could never be considered highly maneuverable at higher speeds. At lower speeds, differential propeller thrust is quite an effective adjunct due to the relatively large separation of the two propellers.

In order to assess the relative merits of potential rudder schemes or combinations there of for the OHF, we must first quantify their force and moment coefficients.

<u>Strut Rudder on Center Strut</u>

If a trailing edge strut rudder of the same aspect ratio were placed on the center strut of the OHF as is on the SWATH 6A, the effective area would be 137.6 square feet. Adjusting the value of $Y'_{\delta r}$ for the SWATH 6A from reference 4 by the ratio of areas and the square of their respective non-dimensionalizing length we get $Y'_{\delta r}$ = .00443.

The distance from the center of gravity to the rudder post divided by the hull length is - 0.249 for the OHF model as built and - 0.324 for the OHF model with the outer hulls moved forward 50 feet. This makes $N'_{\delta r}$ = - .0011 for OHF model as built and $N'_{\delta r}$ = - .001435 for OHF model with outer hull moved forward fifty feet.

Stabilizer Steering

The rudder derivatives for stabilizer steering are more difficult to estimate. The only tests have been made on the SWATH 6B and T-AGOS 19. The important pressure force may be highly dependent on the stabilizer aspect ratio or more likely on its root chord. To this author's knowledge there is no available data on the effect of aspect ratio or root chord on the pressure force. To make a reasonable estimate we look to the tests on the SWATH 6B reported in reference 6.

The equivalent lift curve slope is made up of the horizontal component of lift on the stabilizers plus the concomitant pressure force on the hull, the values of which are 1.043 and 1.117 respectively for the SWATH 6B, based on two 235 square feet 13.1 foot chord stabilizers. For the OHF the stabilizer for the same area would have a 25 foot span and chord of 9.4 feet. Only two thirds of the span can have a control flap in order to avoid creating a pressure force on the center hull which would counteract that on the outboard hulls.

To get the equivalent lift curve slope for the OHF we will start with that of the SWATH 6B, increase it 50% (due its better aspect ratio) and then multiply it by two thirds (since only 2/3 of the stabilizer is controlled) we get

$$(C_{L_\alpha})\text{lift} = (1.043)(1.5)(2/3) = 1.043$$

To estimate the pressure force, we multiply the SWATH 6B pressure force by the ratio of their respective root chords.

$$(C_{L_\alpha})\text{pressure} = 1.117\ (9.4/13.1) = 0.802$$

The total $C_{L_\alpha} = 1.845$ which translates to $Y'_{\delta_r} = .0041$.

The estimated distance from the center of gravity divided by the hull length is - 0.35 for the OHF model as built and - 0.27 with the outer hulls moved 50 feet forward. This translates into $N'_{\delta_r} = -\ .001435$ for the OHF model as built and $N'_{\delta_r} = -\ .00111$ with the outer hulls moved 50 feet forward.

<u>Rudders on the outer hulls</u>

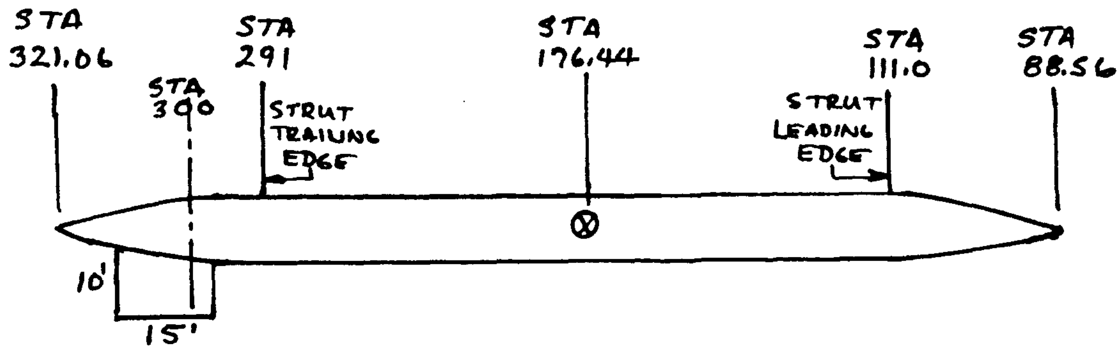

Figure 7. Rudder location on Outer Hull

The placement of the rudders on the outer hull is shown below in figure 7. The span of the rudder is limited to 10 feet so as not to exceed the draft of the center hull. The C_{L_δ} of the rudders is estimated as 2.5. This translates to a $Y'_{\delta r}$ = -.0071. The non-dimensional moment arm of the rudder is - 0.38 and - 0.29 which makes $N'_{\delta r}$ = - .0027 and - .00205 for the OHF model as built and with the outer hulls 50 feet forward respectively.

Overhung rudder aft of propeller

Figure 8 below shows the alterations to the center hull necessary for the placement of the rudder aft of the propeller.

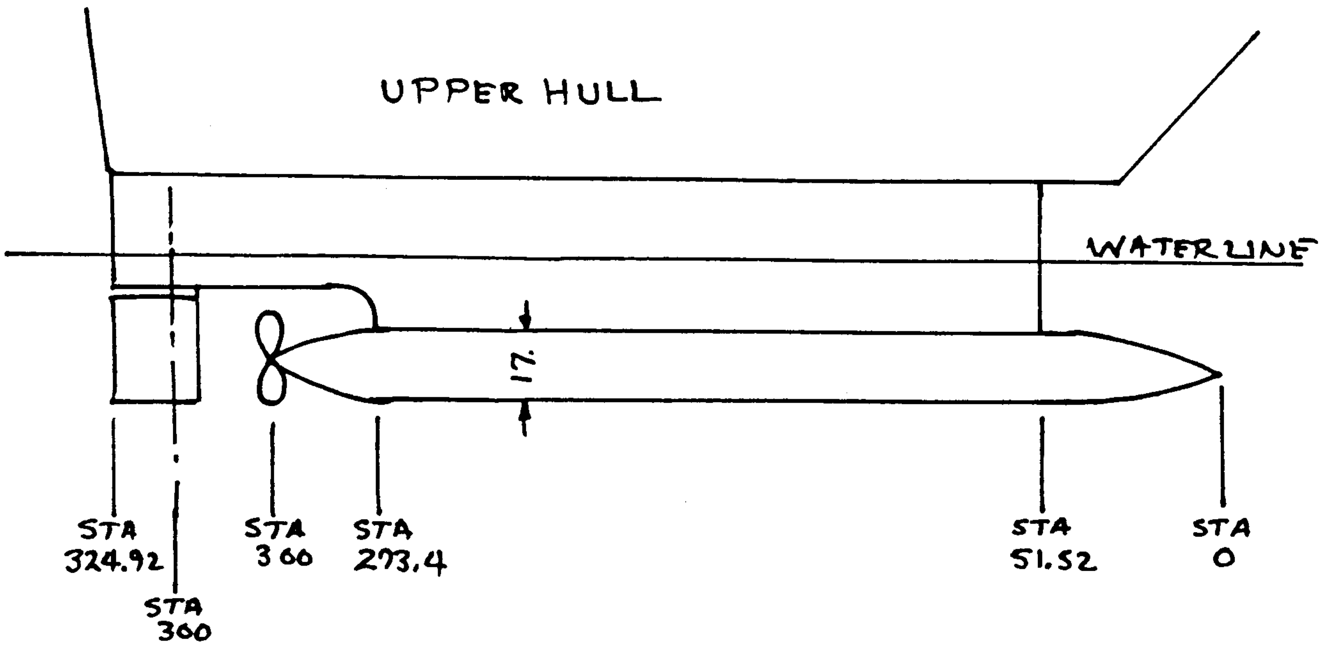

Figure 8. Overhung rudder configuration

In order to maintain the same buoyancy in the shortened center hull, it was necessary to increase its diameter 0.75 feet.

This increase in hull diameter increased the draft 0.75 feet as the same strut was maintained. This also shifted the center of gravity 6.17 feet forward. The rudder in figure 8 is identical to that on the SWATH 6E and is assumed to have the same C_{L_δ} of 2.5 as was measured on the SWATH 6E. This translates into a $Y'_{\delta r}$ = .00546. The non-dimensional moment arm of the rudder is - 0.446 and - 0.509 which makes $N'_{\delta r}$ = - 0.00243 and - 0.00278 for the OHF as built and with the outer hulls 50 feet forward respectively.

Using the values of $Y'_{\delta r}$ and $N'_{\delta r}$ (which are summarized in Table B-1, Appendix B) the minimum turn diameter for the OHF is calculated. The spade type rudders are considered capable of generating a lift coefficient of 0.524 times their respective lift curve slope. This is not unreasonable for a Shilling type rudder. On the other hand the trailing edge strut rudder and the stabilizer rudder are considered capable of a lift coefficient of only 0.349 times their respective lift curve slope.

The minimum turn diameter for six different rudder configurations for both the OHF as built and the OHF with the outer hulls moved forward 50 feet were determined* and tabulated Table 4, Appendix B. The results are also shown graphically in Figure 9 for the OHF model as built.

The turn radius with an overhung rudder aft of the propeller is the smallest and can be further reduced by 27% by adding spade rudders to the outer hull.

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* The worksheets on which this was done are included in Appendix B.

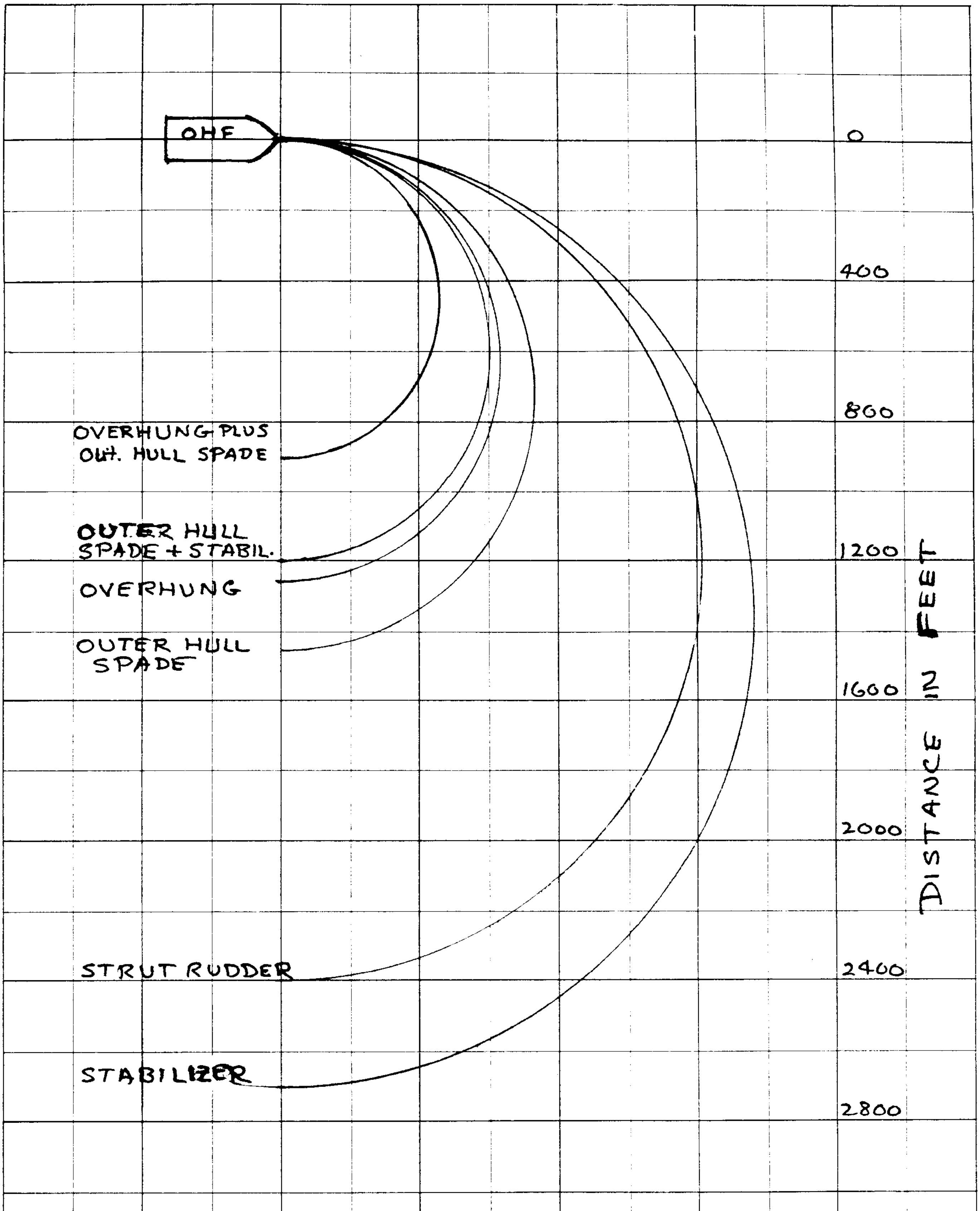

FIGURE 9. MINIMUM TURN DIAMETER OF OHF (AS BUILT) FOR DIFFERENT RUDDER CONFIGURATION

W. O'N
3/14/88

Conclusions and Recommendations

As a result of this work the following conclusions and recommendations are offered.

1. Little can be done by practical changes to the geometry of a conventional SWATH to greatly reduce its inherent stability in order to make it more maneuverable. Some reduction in inherent stability can be obtained. Every 0.01 reduction in the strut length to hull length ratio results in a 1.33% reduction in turn diameter; and for every 1% of strut length that the center of the strut is moved forward (relative to the center of gravity), there is a 3.75% reduction in turn diameter.

2. Rudders which are near or pierce the free surface lose much of their effectiveness at higher speeds due to the surface distortion which tends to unwet the rudder.

3. The expressions for the lateral derivatives of a SWATH developed in this paper can be used for trending and comparative studies until better ones are developed or a verified analytical approach is developed.

4. An overhung rudder aft of propeller, followed by spade rudders below the outer hulls are the two most effective of the rudder schemes studied.

5. The OHF is inherently easier to turn than a conventional SWATH. With a single overhung rudder the OHF turn radius is about the same as that of the SWATH 6E with two overhung rudders of the same size even though the OHF is longer and heavier than the SWATH 6E.

6. The analytical approach of Hirano and Fukushima (ref. 2) shows great promise and should be looked into further to resolve the questions raised in this paper. (Perhaps all that is needed is some redefinition of certain parameters or some minor empirical adjustments.)

References

1. "Comment and Notes on the Control of SWATH Ships"by William C. O'Neill, April 1987.

2. "A Calculation of Hydrodynamic Forces Acting on a Semi-submerged Catamaran in Maneuvering Motion" by Hirano and Fukushima. Transactions of West Japan Japan Society of Naval Architects No 56, August 1978.

3. "A Non-linear Wing Theory and Its Application to Rectangular Wings of Small Aspect Ratio" by W. Bollay. ZAMM 1939.

4. "A Model Series for SWATH Ship Maneuvering Performance Predictions" by Waters and Bochinski. David Taylor Naval Ship Research and Development Center report number SPD-698-04 June 1983.

5. "Principles of Naval Architecture" SNAME 1967.

6. "Results of Stabilizer Steering Performance Experiments Conducted on the SWATH-6B Model" by Waters and Hickok. David Taylor Naval Ship Research and Development Center report number 86/SPD-698-05, August 1986.

7. "T-AGOS 19 Contract Design Evaluation Report: Ship Maneuvering Performance and Rudder System Selection Design History" by Waters and Hickok. David Taylor Research Center report number DTRC-87/SHD-1184-07 September 1987.

APPENDIX A

Comparison of Predicted to Measured Lateral Derivatives and Index of Stability

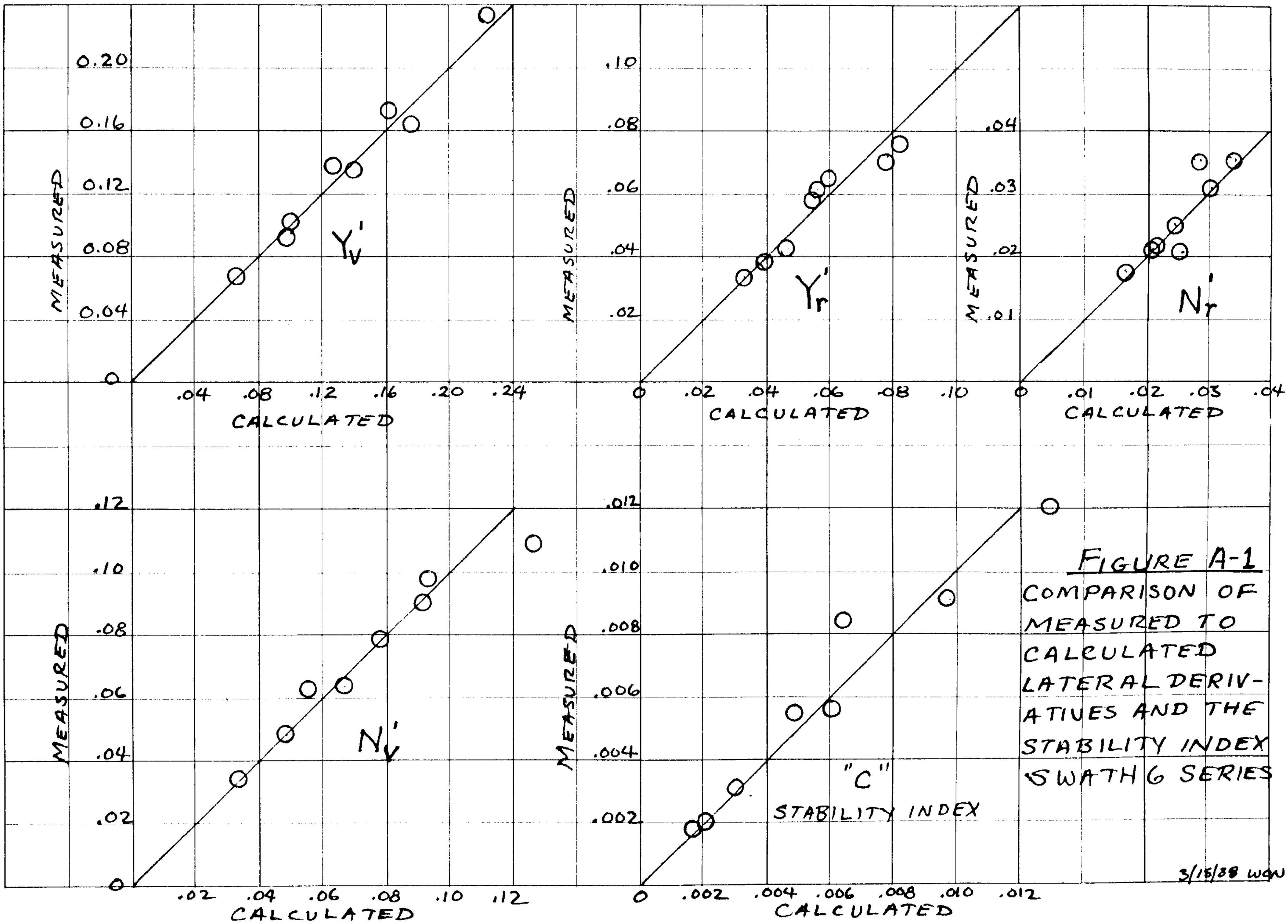

FIGURE A-1
COMPARISON OF MEASURED TO CALCULATED LATERAL DERIVATIVES AND THE STABILITY INDEX SWATH 6 SERIES

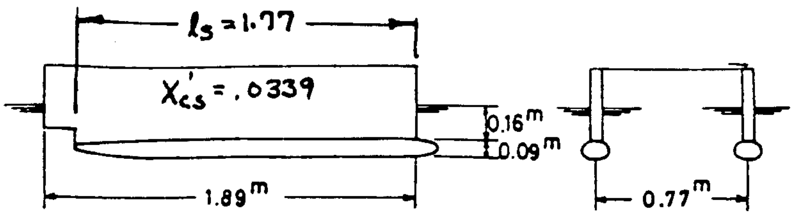

Fig. 6(a) SSC "A"

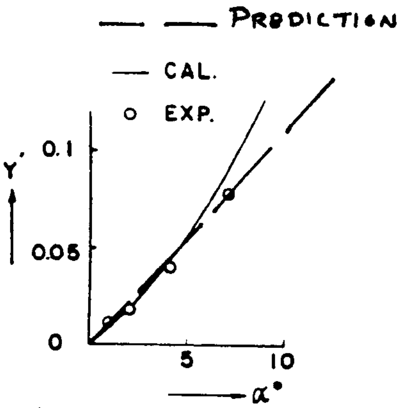

Fig. 6(b) Swaying Force as Function of Drift Angle (SSC "A")

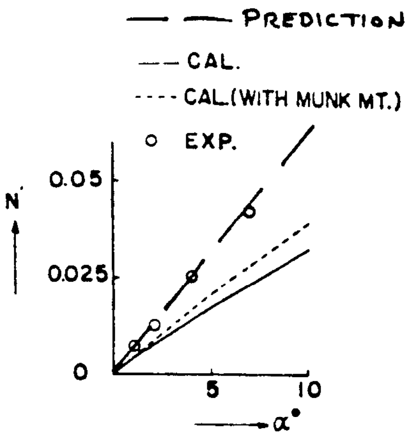

Fig. 6(c) Yawing Moment as Function of Drift Angle (SSC "A")

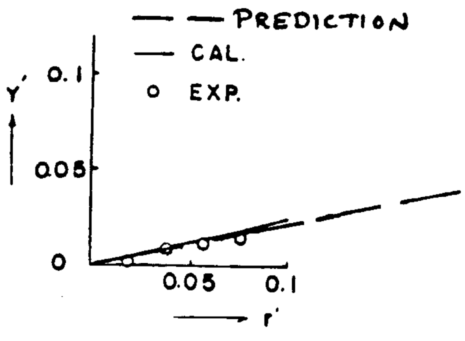

Fig. 6(d) Swaying Force as Function of Turning Rate (SSC "A")

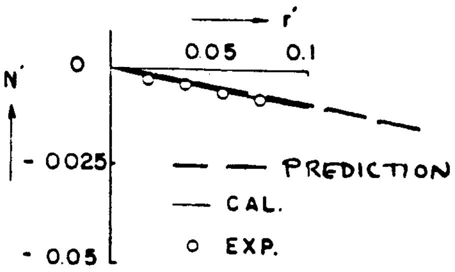

Fig. 6(e) Yawing Moment as Function of Turning Rate (SSC "A")

Figure A-2. Predictions From This Paper Superimposed On The Results Of Model SSC"A" Of Reference 2.

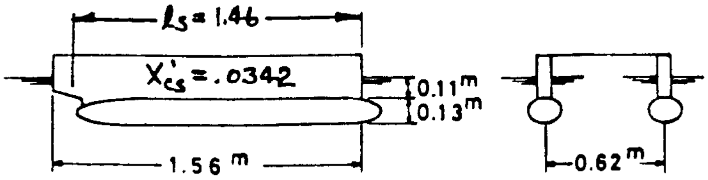

Fig. 8(a) SSC "C"

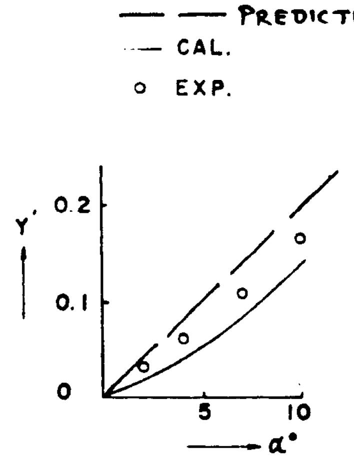

Fig. 8(b) Swaying Force as Function of Drift Angle (SSC "C")

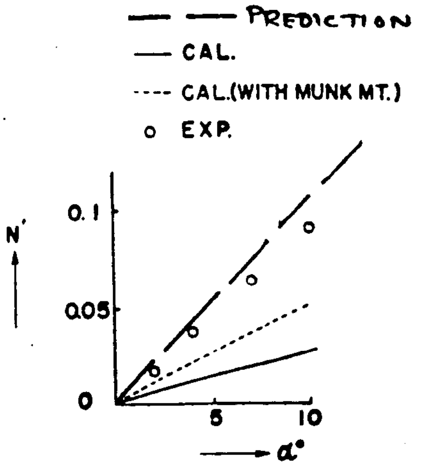

Fig. 8(c) Yawing Moment as Function of Drift Angle (SSC "C")

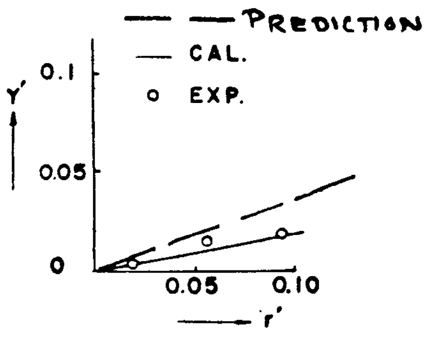

Fig. 8(d) Swaying Force as Function of Turning Rate (SSC "C")

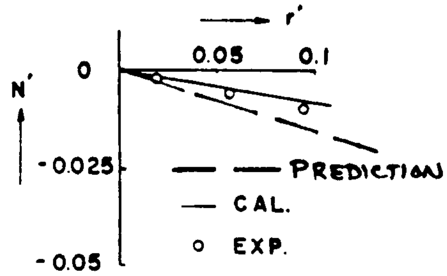

Fig. 8(e) Yawing Moment as Function of Turning Rate (SSC "C")

Figure A-3. Predictions From This Paper On The Results Of Model SSC"C" Of Reference 2.

TAGOS-19 Worksheet (All data from reference 7)

$l_s = 190'$

c.g at station 91.9

center of strut ... 85.0

Draft varies along hull

use $A.R = \frac{\text{lateral Area}}{l_s^2} = 0.1245$

$X'_{cs} = \frac{91.9-85.0}{190} = .0363$

$m' = \text{mass}/\tfrac{1}{2}\rho l^3 = .0343$

$\Delta Y'_v$ (prop guard) $= \frac{-5.0(1.7\times16)-2.5(43)}{(190)^2} \times 2 \text{ sides} = -.0135$

$X'_{pg} = \frac{91.9-211.2}{190} = -0.625$

$\Delta Y'_v$ (stabilizers) $= \frac{-C_{L\delta} \times S_s \times \sin 20°}{l_s^2} = -.0140$ $C_{L\delta} = 3.55$

$X'_{STAB} = -0.34$

$\Delta Y'_v$ (canards) $= \frac{-C_{L\delta} \cdot S_c \times \sin 20°}{l_s^2} = -.0123$

$X'_{CAN} = 0.3$[illegible]

Derivative	basic	Stabil	Canard	Ship, no prop guard	Prop Guard	Baseline	Ref (7) Measured Baseline
Y_v	-.09285	-.0140	-.0123	-.1191	-.0135	-.1326	-.1331
N_v	-.05475	+.0048	-.0038	-.0538	.0085	-.0453	-.0416
Y_r	+.03108	+.0048	-.0038	+.0321	.0085	.0406	.0448
N_r	-.0204	-.0016	-.0012	-.0232	-.0053	-.0285	-.0254
"C"				.00264	—	.00406	.00382
$(Y_v N_{\delta r} - N_v Y_{\delta r})$*				.001758	—	.00163	.00150
$\delta(R/L)$				1.50 ①	—	2.49	2.46

* $Y_{\delta r} = .0223$ (measured)

$N_{\delta r} = -.00469$ (measured)

① ADDING PROPELLER GUARD DECREASED TURNING PERFORMANCE 40% (calculated) compared to 38% reported in reference (7)

APPENDIX B

Calculations of OHF Lateral Derivatives
Indices of Stability and Turn Rates
for Various Rudder Configurations

1	STRUT RUDDER					
Rudder included in basic unappend.	OHF MODEL AS BUILT			OHF MODEL O.H 50' FWD		
	UNAPPEND. SHIP	Δ RUDDER	TOTAL	UNAPPEND. SHIP	Δ RUDDER	TOTAL
Y'_v	-.0279	—	-.0279	-.0279	—	-.0279
N'_v	-.0095	—	-.0095	-.00959	—	-.00959
Y'_r	.00718	—	+.00718	.0070	—	.0070
N'_r	-.0032	—	-.0032	-.00292	—	-.00292
STAB. INDEX "C"	.0000919			.0000824		
$Y'_{\delta r}$	.00443			.00443		
$N'_{\delta r}$	-.001101			-.001435		
$Y'_v N'_{\delta r} - N'_v Y'_{\delta r}$	.0000718			.0000825		
δ_r R/L	1.28			1.00		
MINIMUM TURN DIA	2383 FT.			1862 FT		

2	SPADE RUDDERS ON OUTER HULL					
	O.H.F. MODEL AS BUILT			OHF MODEL O.H. 50' FWD		
	UNAPPEND SHIP	Δ RUDDER	TOTAL	UNAPPEND SHIP	Δ RUDDER	TOTAL
Y'_v	-.0279	-.0071	-.0350	-.0279	-.0071	-.0350
N'_v	-.0095	+.0027	-.00[illegible]8	-.00959	.00205	-.00754
Y'_r	.00718	.0027	.00988	.0070	.00205	.00905
N'_r	-.0032	-.001026	-.004226	-.00292	-.00059	-.00351
STAB INDEX "C"	.0001682			.0001391		
$Y'_{\delta r}$	.0071			.0071		
$N'_{\delta r}$	-.0027			-.00205		
$Y'_v N'_{\delta r} - N'_v Y'_{\delta r}$	.0001428			.0001253		
δ_r R/L	1.17			1.11		
MINIMUM TURN DIA	1452 FT			1378 FT		

WORKSHEET TO DETERMINE TURNING CHARACTERISTICS

5	OVERHUNG RUDDER CENTER STRUT					
Rudder included in basic	OHF MODEL AS BUILT			OHF MODEL O.H 50' FWD		
	UNAPPEND. SHIP	RUDDER	TOTAL	UNAPPEND. SHIP	RUDDER	TOTAL
Y'_v	-.0285	~	-.0285	-.02848	—	-.02848
N'_v	-.00926	~	-.00926	-.00932	~	-.00932
Y'_r	.00895	~	.00895	.00882	—	.00882
N'_r	-.00359	~	-.00359	-.00339	~	-.00339
STAB. INDEX "C"	.0001212			.0001144		
$Y'_{\delta r}$	.00546			.00546		
$N'_{\delta r}$	-.00243			-.00278		
$Y'_v N'_{\delta r} - N'_v Y'_{\delta r}$	.001199			.00013		
δ_r R/L	1.01			0.88		
MINIMUM TURN DIA	1254 FT			1092 FT		

6	OVERHUNG RUDDER PLUS OUTER HULL SPADES					
	O.H.F. MODEL AS BUILT			OHF MODEL O.H. 50' FWD		
	UNAPPEND SHIP	Δ RUDDER	TOTAL	UNAPPEND SHIP	Δ RUDDER	TOTAL
Y'_v	-.0285	-.0071	-.0356	-.02848	-.0071	-.03558
N'_v	-.00926	.0027	-.00676	-.00932	+.00205	-.00727
Y'_r	.00895	.0027	.01164	.00882	+.00205	+.01087
N'_r	-.00359	-.001026	-.00461	-.00339	-.00059	-.00398
STAB INDEX "C"	.0001964			.0001705		
$Y'_{\delta r}$	.01256			.01256		
$N'_{\delta r}$	-.00513			-.00483		
$Y'_v N'_{\delta r} - N'_v Y'_{\delta r}$	.0002675			.0002632		
δ_r R/L	0.734			.648		
MINIMUM TURN DIA	912 FT			804		

WORKSHEET TO DETERMINE TURNING CHARACTERISTICS

3	STABILER STEERING					
	OHF MODEL AS BUILT			OHF MODEL O.H 50' FWD		
	UNAPPEND. SHIP	Δ RUDDER	TOTAL	UNAPPEND. SHIP	Δ RUDDER	TOTAL
Y'_v	-.0279	-.0023	-.0302	-.0279	-.0023	-.0302
N'_v	-.0095	.0008	-.0087	-.00959	.0006	-.00899
Y'_r	.00718	.0008	.00798	.00700	.0006	.0076
N'_r	-.0032	-.0003	-.0035	-.00292	-.0002	-.00312
STAB. INDEX "C"	.0001151			.0001005		
$Y'_{\delta r}$	.0041			.0041		
$N'_{\delta r}$	-.00144			-.00111		
$Y'_v N'_{\delta r} - N'_v Y'_{\delta r}$	.000792			.0000704		
δ_r R/L	1.454			1.428		
MINIMUM TURN DIA	2707 FT			2658 FT		

4	STABILIERS PLUS OUTER HULL SPADE RUD.					
	O.H.F. MODEL AS BUILT			OHF MODEL O.H. 50' FWD		
	UNAPPEND SHIP	Δ RUDDER	TOTAL	UNAPPEND SHIP	Δ RUDDER	TOTAL
Y'_v	-.0279	-.0094	-.0373	-.0279	-.0094	-.0373
N'_v	-.0095	+.0035	-.0060	-.00959	+.00265	-.00694
Y'_r	.00718	+.0035	.01068	.0070	+.00265	.00965
N'_r	-.0032	-.00133	-.00453	-.00292	-.00079	-.00373
STAB. INDEX "C"	.0001916			.0001582		
$Y'_{\delta r}$	.0112			.0112		
$N'_{\delta r}$	-.00414			-.00316		
$Y'_v N'_{\delta r} - N'_v Y'_{\delta r}$	.0002216			.0001956		
δ_r R/L	0.865			0.809		
MINIMUM TURN DIA	1218 FT			1139 FT		

WORKSHEET TO DETERMINE TURNING CHARACTERISTICS

B-4

	Type of Rudder	OHF Model As Built				OHF Model With Outer Hulls 50' Forward			
		$Y'_{\delta r}$	$N'_{\delta r}$	X'_R	Minimum* Diameter	$Y'_{\delta r}$	$N'_{\delta r}$	X'_R	Minimum* Diameter
1	Strut Rudder	.00443	-.0110	-.249	2383 ft.	.00443	-.001435	-.324	1862 ft.
2	Outer Hull Spade Rudders	.00710	-.0027	-.38	1452	.00710	.00205	-.29	1378
3	Stabilizer Steering	.0041	-.00144	-.350	2707	.0041	.00111	-.270	2658
4	Stabilizer + Outer Hull Spade Rudders	.0112	-.00414	--	1218	.0112	.00316	--	1139
5	Overhung Rudder	.00546	-.00243	-.446	1254	.00546	.00278	-.509	1092
6	Overhung + Outer Hull Spade Rudders	.01256	-.00513	--	912	.01256	.00483	--	804

* Calculated assuming spade rudders maximum force coefficient = (30/57.3) $Y'_{\delta r}$ and assuming strut and stabilizers maximum force coefficient = (20/57.3) $Y'_{\delta r}$

Note: Non-dimensional quantities are based on the OHF center hull length of 324.92 feet.

TABLE B-1. Rudder Characteristics and Minimum Turn Diameter for the OHF with Various Rudder Schemes.