Technical Paper

Transactions of the Society of Naval Architects of Korea
Vol.29, No. 3, August 1992
大韓造船學會論文集
第 29 卷 第 3 號 1992 年 8 月

A Comparison of Hydrodynamic Characteristics of Single and Tandem Strut SWATH Ships

by

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하나 또는 두개의 지주를 갖는 소수선면 쌍동선의 유체동역학적 특성 비교

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Abstract

This report is to provide a comparison of the hydrodynamic characteristics of a single strut SWATH(Small Waterplane Area Twin Hull) model and a tandem(twin) strut SWATH model. The hydrodynamic characteristics included are the resistance in calm water, 6 degree freedom of motion responses in stationary and with forward speeds, and wave loadings etc. All these quantities are measured in the towing tank and compared with the computational results. Based on the present study, the pros and cons for single and tandem strut SWATH designs are clarified and some design suggestions are made.

요 약

하나 또는 두개의 지주를 가지는 소수선면 쌍동선의 유체동역학적 특성에 대한 비교 연구결과를 다루었다. 두 모형선으로 정수중에서의 저항, 파랑중에서 정지 및 속도를 가질 때의 6 자유도 운동응답, 그리고 파랑하중등을 수조 실험실에서 측정하였으며 수치해석결과들과 자세하게 비교하였다. 본 연구 결과에 의거하여 두 SWATH 모델들의 장단점을 열거하였으며 이는 SWATH선의 설계 고려에 유익하게 쓰여질 수 있다고 생각된다.

Manuscript received : February 20, 1992, revised manuscript received : May 11, 1992.

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Nomenclature

2b(B)	spacing between the centreplanes of two demihulls
$Fn=U/\sqrt{gL_b}$	Froude number based on the body length(L_b)
$g=9.807$	acceleration due to gravity
L_w	wave length
M3	bending moment at mid point of the cross-deck section
$M3'=M3/g\Delta\zeta_a$	non-dimensional bending moment
V3	vertical shear force
$V3'=V3L_b/g\Delta\zeta_a$	non-dimensional vertical shear force
x_a	surge amplitude
y_a	sway amplitude
z_a	heave amplitude
$X'=x_a/\zeta_a$	dimensionless surge response
$Y'=y_a/\zeta_a$	dimensionless sway response
$Z'=z_a/\zeta_a$	dimensionless heave response
ρ	density of water
ζ_a, ζ_w	wave amplitude and height, respectively
θ_a	pitch amplitude
ϕ_a	roll amplitude
Ψ_a	yaw amplitude
$\Theta'=\theta_a g/\zeta_a\omega_0^2$	dimensionless pitch response
$\Phi'=\phi_a g/\zeta_a\omega_0^2$	dimensionless roll response
$\Psi'=\Psi_a g/\zeta_a\omega_0^2$	dimensionless yaw response
ω	encounter wave frequency
ω_0	wave frequency
$\omega'=\omega\sqrt{L/g}$	dimensionless encounter wave frequency
Δ	displacement

Other symbols not listed here are mentioned where they first appear in the text and the appropriate non-dimensionalisation in the axis of figures is made as given above.

1. Introduction

The excellent seakeeping qualities of SWATH ships have been demonstrated by the SWATH ships already at sea, and by experimental and analytical studies[1-3]. However, the small number of SWATHs at sea(23 SWATH ships at the time of writing as seen in Table 1) is evidence that the marine community has not been convinced of the utility of the concept. There are several possible reasons for this state of affairs. Perhaps the most optimistic is the view of Betts[4] that 'any new invention or major innovation seems to take around 20 years to mature and become accepted'. This would mean that SWATHs is now close to full acceptance and that the uncertainties of previous years are a natural part of the development process.

Fig. 1 shows the SWATHs build profile for the last two decades and SWATHs under construction or ordered to build presently. It seems that the success of the FBM Patria, Navateck I and USNS Victorious(T-AGOS 19) secured the more new orders of SWATHs in 1991-1992. These new orders are as follows:

-four US NAVY SWATHs of TAGOS-20, 21

Table 1 Configurations of existing or newly building SWATH ships

Name	Builder/Designer	Design Role	Speed Knots	Disp. Tons	Power KW	Length O.A. (m)	Breadth O.A. (m)	Draft m	Year	Strut
Twin Drill	Boele Shipyard	Seabed operations	8.0	1200	1395	40.0	17.1	5.2	1969	S*
Trisc 1	USA	Experimental	8.0	1.18	9	6.1	2.4	0.6	1971	S
Kaimalino	U.S. Coast Guard	Naval workboat	25/18	193/224	3150	26.8	13.7	4.6	1973	T^
Marine Ace I	Mitsui Engineering	Experimental	17.3	18.4	300	12.3	6.5	1.6	1977	T
Marine Ace II	Mitsui Engineering	Experimental	15.4	22.2	300	12.3	6.5	1.6	1978	S
Seagull I	Mitsui Engineering	Fast ferry	27.1	≈343	6075	35.9	17.1	3.2	1979	S
Ohtori	Mitsubishi	Hydrographic survey	20.6	239	2850	39.3	15.6	3.2	1980	S
Kotozaki	Mitsui Engineering	Hydrographic survey	20.5	236	2850	27.0	12.5	3.2	1980	S
Betsy	SWATH Ocean	Sport fishing	18.0	53	638	19.3	9.1	2.1	1981	S
Charwin	St. Augustine Trawler	Scallop fishing	9.0	205	724	24.4	12.2	3.4	1983	S
Kaiyo	Mitsui Engineering	Diving support	14.1	3500	5520	60.0	28.0	6.3	1984	S
Halcyon	SWATH Ocean	Demonstration	22.4	43/57	765	18.3	9.2	2.2	1985	S
Marine Wave	Mitsui Engineering	Leisure boat	20.5	25.4	375	15.1	6.2	1.6	1985	S
Chubasco	SWATH Ocean	Yacht	20.0	56/79	1125	21.9	9.4	2.1	1987	S
Sun Marina	Mitsui Engineering	Leisure boat	20.5	25.4	450	15.0	6.4	1.6	1987	S
Samhach	Yarrow Shipbuilder	Test bed	6.0	3.5	5				1988	S
Frederick Creed	SWATH Ocean	Ocean survey	26.5	75	1620	20.0	10.7	2.4	1989	S
Bay Queen	Mitsui Engineering	Multi-purpose	21.6	40	705	18.0	6.8	1.6	1989	S
Victorious (T-AGOS 19)	McDermott Shipyard	Sub sea surveilliance	9.6	3450	1194	70.7	28.7	7.5	1989	S
Patria	FBM Marine	Fast ferry	30.0	117/172	4100	36.5	13.0	2.7	1989	S
Navatek I	Navatek Ships	Inter island ferry	17.0	371	2025	43.0	16.2	4.3	1989	T
SWATH Ali	MacGregor Bros.	Creel fishing	8.0	20	105	11.0	5.0	1.6	1989	S
Seagull II	Mitsui Engineering	Fast ferry	30.6	≈345	8160	39.3	15.6	3.2	1989	S
Diana	Mitsui Engineering	Party boat	19.2	52	552	19.4	6.8	1.6	1990	S
Hibiki (AOS 5201)	.Mitsui Engineering	Sub sea surveilliance	11.0	≈3750	2239	67.0	29.9	7.5	1990	S
Jimani	Semi Submerged Ship	Demonstration	35.0	≈1	93	5.2	2.4	dual	1991	S
Pursuit	SWATH Ocean	Demonstration	22.0	13	242	10.9	5.0	1.0	1991	S
Able (T-AGOS 20)	McDermott Shipyard	Sub sea surveilliance	9.6	3360	1194	70.7	28.7	7.5	1991	S
Effective (T-AGOS 21)	McDermott Shipyard	Sub sea surveilliance	9.6	3360	1194	70.7	28.7	7.5	1991	S
Loyal (T-AGOS 22)	McDermott Shipyard	Sub sea surveilliance	9.6	3360	1194	70.7	28.7	7.5	1991	S
Harima (AOS 5202)	Mitsui Engineering	Sub sea surveilliance	11.0	≈3750	2239	67.0	29.9	7.5	1991	S
Houston Pilot Boat	SWATH Ocean		23.0	79	1447	20.0	11.3	2.4	1992	S
Chubasco 2	SWATH Ocean		25.0	165	3311	27.6	13.7	2.7	1992	S
Alison	Metal Boat Inc	Party fishing	14.8	67	672	26.5	11.0	2.1	1992	T
Radison Diamond	Rauma Yard	Cruiser	12.5	≈11000	11400	129.0	32.0	8.0	1992	S
Radison Luby	Rauma Yard	Cruiser							1993	S
Impeccable (T-AGOS 23	Tampa Shipyards	Sub sea surveilliance	12.0	5460	3730	85.8	29.2	7.9	1994	S

* S- Single Strut, ^ T-Twin or Tandem Strut

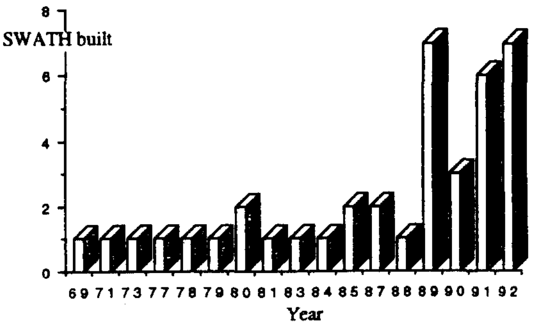

Fig. 1 SWATH ship build profile

and 22 with McDermotts of Amelia, Louisiana, and of TAGOS-23 with Tampa Shipyards.

—three Navateck SWATHs for Hawaiian Cruises Ltd(not confirmed),

—two 18,400 grt SWATH cruisers by Rauma Yards for Diamond Cruise Ltd, Finland,

—a 67-ton, tandem strut SWATH by the U.S., Metal Boat Inc.,

—a second Creed-class SWATH for the Houston Pilots Association and a new, larger Chubasco 2 by SWATH Ocean Ltd.,

Recently, the image of the SWATH concept seems to be changing in terms of speed and size. It should be credited to F.B.M.Ltd., U.K., in that the 170 tonne SWATH PATRIA(no fins) recorded a sea trial speed of 32.1 knots [3] which is much beyond the speed(30 knots) for most

SWATH designers to believe to be a limit for the SWATH concept. Further, SWATH Ocean System Ltd., U.S.A., released a 40 knot SWATH Ferry design[5]. If the stabilising fins can be removed from the SWATH concept, the weight and also construction cost of the SWATH ship can be much reduced and this will be a great breakthrough in SWATH design from the conventional concept. The first 18,400 grt SWATH cruiser, Radison Diamond, is under construction at Finland's Rauma Yards, which is due to be delivered in May 1992 [6]. This is a largest SWATH ship ever built and after successful operations, numerous advantages of the SWATH concept will be exploited in order to help enlarge the size of SWATH ships such as large car ferry and cruiser, etc.

Choice of Single and Tandem Strut

Selection of the number of struts per hull is one of the fundamental choices available to the SWATH designer. As seen in Table 1, four of 37 SWATH ships have twin or tandem struts on each hull and the remainings have a single long or short strut on each hull. The choice between single and tandem struts for SWATH ships has been considered in several papers[7－9]. The single strut version has been most widely adopted so far because of various practical aspects such as simplicity of design, better accessibility to the lower hulls for maintenance, greater structural strength, large payload capacity and greater static stability. This greater static stability can reduce the risk of possible heeling due to a sudden shift of many passengers(important for passenger ships) or other items of cargo payload. However, aforementioned 3 new order SWATHs designed by Navatek Ships Ltd are all tandem strut designs.

Table 2 Main particulars of MARINE ACE two versions

	Twin strut	Single Strut
Length b.p.(m)	11.00	
Breadth, max, (m)	6.50	
Depth (m)	2.70	
Draft (m), fully loaded	1.55	
Displacement at full load(ton)	18.4	22.2
Waterplane area at load line(m^2)	4.9	10.3
Natural periods (sec)		
Heave	5.5	3.9
Pitch	4.8	4.5
Roll	11.2	4.7
GM_T(m)	0.5	2.1

Mitsui Engineering and Shipbuilding Co., Ltd. built a twin strut SWATH, 'Marine Ace Ⅰ', and later converted it to a single strut version, Marine Ace Ⅱ, by filling the gap between the fore and aft struts to make a smooth continuous strut. Extensive sea trials for the both versions were conducted and the results are reported in Ref. [8], without much detail. Table 2 shows a comparison of main particulars for both versions of 'MARINE ACE', taken from the reference. The waterplane area of the tandem version is less than one half that of the single version. The reduction in waterplane area changes the restoring force and moment and, consequently, alters the natural periods in heave, pitch and roll motions as shown in the Table. Also, this reduced waterplane area will enhance seakeeping performance at the cost of the TPC and a stiffer roll motion for the single version is expected due to the shorter roll period. In general, the tandem struts version has lower side loads and motions at rest, and a shorter turning radius compared to the single strut version.

A tandem strut SWATH model was built and tested to measure the calm water resistance, zero-speed motion responses in head, quartering and beam seas, wave loadings in quartering and beam seas, and forward-speed motion responses in head seas. Then, the tandem strut SWATH model was converted to a single strut version in the same manner as was done for 'Marine Ace' and the same tank tests were done as with the tandem strut SWATH model. All these hydrodynamic quantities measured are compared with computational results using the several codes developed by the author. Most of the results reported herein have been published separately under different aims and titles[10－15] and all materials related to the aforementioned matters are put together in a more comprehensive manner in this paper. Therefore, the aim of this paper is to provide a comparison of the aforementioned hydrodynamic characteristics for a single strut SWATH model and a tandem (twin) strut SWATH model. Based on the present study, the pros and cons for single and tandem strut SWATH designs are clarified and some design suggestions are made.

2. Description of Model SWATH1 and SWATH3

The model SWATH1 is a tandem strut configuration. The lower portion of the demihull(referred to as the submerged body) has circular cross sections with ellipsoidal and tapered ends. The upper portion of the demihull, referred to as the strut, has the same water line at all drafts and is of airfoil section. The forward and aft struts are identical to each other.

The SWATH1 tandem strut model was converted by inserting a parallel section between the maximum chord of the fore and aft struts on the demihull to make a continuous, smooth strut and designated as SWATH3. Hence, the waterplane area is nearly doubled from that of the SWATH1. Some dimensions and principal coefficients for the both models are listed in Table 3 together with the comparison of the natural periods for heave, pitch and roll. All the experiments reported in this paper were conducted with the two models having no fins attached.

Table 3 Principal Dimensions of Two SWATH Models

Model	SWATH1-C8*	SWATH3-C3
Length of Body, L_b	1.51	
Diameter of Body, Di_b	0.0892	
Max. Beam of Strut, T_m	0.05	
C_p of Body	0.9	
C_{wp} of Strut	0.665	0.884
$B_1=4b/L_b$	0.947	
Draft(m), T	$2.0\ Di_b=0.1784$	
Waterplane Area	0.0532	0.1020
Length of Strut, L_s	0.4	1.155
Wetted Area, S	1.0252	1.1078
Displaced Volume, ∇	0.02175	0.0261
GM_T	0.204	0.386
GM_L	0.229	0.207
KG	0.1753	0.197
KB	0.064	0.0757
L.C.G from nose	0.7325	0.7325
I_{44} in air	3.5231	3.3137
I_{55} in air	3.9574	2.991
I_{66} in air	6.2889	5.452
Natural Periods		
Heave(sec), T_z	1.701	1.23
Pitch(sec), T_θ	2.234	1.967
Roll(sec), T_ϕ	2.340	1.512

Units are metric. * C8 indicates a condition numbering tested

Model experiments were carried out at the Hydrodynamics Laboratory of Glasgow University, which is 77m in length, 4.6m in width and 2.4m in water depth.

3. Results and Discussion

3.1 Resistance in Calm Water

Fig. 2 shows the comparison of the total resistance per volume between the single strut SWATH3 and tandem strut SWATH1 models. As with the two Marine Ace versions[8], the resistance of the tandem strut version of SWATH1 is larger than that of the single strut version at all speeds tested. The resistance coefficients(total, residuary and skin-friction) of the SWATH1 and SWATH3 are given in Figs. 3 and 4, respectively, where the resistance is non-dimensionalised by a factor of $0.5\rho U^2\nabla^{2/3}$ in order to compare the two models of having different displacements. The frictional resistance is calculated using the ITTC '57 formulae and the residuary resistance is obtained by subtracting the frictional resistance from the measured total resistance. It can be seen that even at higher speeds, the frictional resistance component is larger than that of the residuary resistance component for the both models. This seems to be the characteristics of the SWATH design since it has a much larger wetted area than that of the equivalent monohull. A tandem strut SWATH ship has a more wetted area than that of a single strut design having the same displacement as each other. This is the very reason for that the SWATH1 model is subject to more resistance than the SWATH3 despite its lower residuary resistance at higher speeds.

Figs. 5 and 6 show the comparisons between

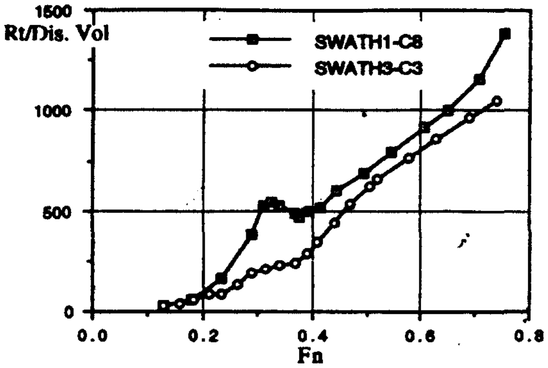

Fig. 2 Comparison of resistance(newton / displaced volume) for SWATH1-C8 and SWATH3-C3

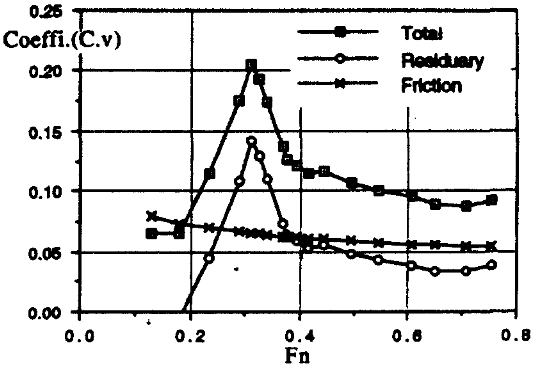

Fig. 3 Total, residuary and skin-frictional resistance coefficients vs Fn For SWATH1-C8

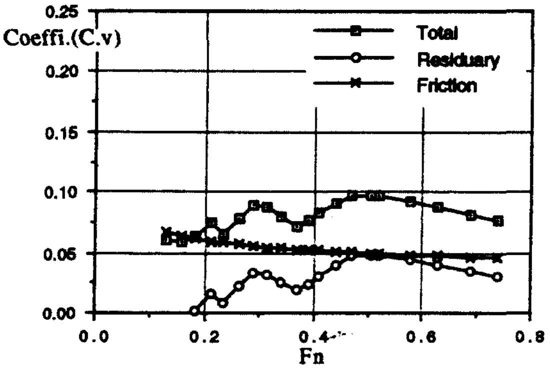

Fig. 4 Total, residuary and skin-frictional resistance coefficients vs Fn for SWATH3-C3

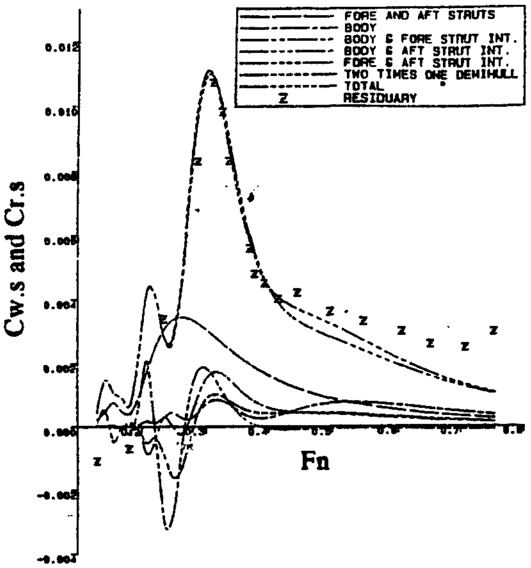

Fig. 5 Wave-making resistance coefficients of SWATH1 -C8 and its component variations together with residuary resistance coefficient vs Fn

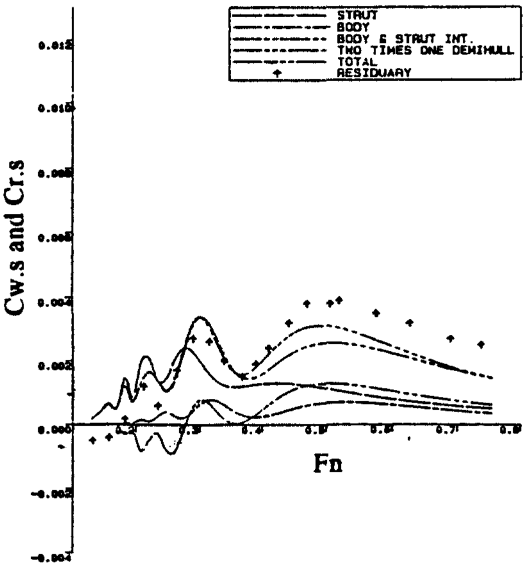

Fig. 6 Wave-making resistance coefficients of SWATH3 -C3 and its component variations together with residuary resistance coefficient vs Fn

the estimated wave-making and measured residuary resistance coefficients for the SWATH1 and SWATH3, respectively. The calculation is based on the modified slender body approximation taking fully into account all interferences between the several components of the SWATH ship[10]. The figures also illustrate the contribution of each component of the models to the total wave-making resistance. A very large peak around Fn=0.3−0.31 with the SWATH1 model is easily understood from Fig. 5 which shows that it is caused by the large wave-making contributions of the struts coupled with unfavourable interferences between the body and the struts and between the forward and aft struts. In particular, the tandem struts, which have low length to thickness ratios compared to the long single strut, contribute significantly to the large peak at that speed. However, the strut with the low length to thickness ratio gives low wave-making resistance at higher speeds and hence, the wave making resistance of the tandem strut SWATH is lower at higher speeds than its counterpart single strut SWATH. The large peak around Fn=0.31−0.39 with the SWATH1 model is much alleviated in waves due to complicated hydrodynamic interference effects[12, 14, 15]. Nevertheless, the resistance of the tandem strut SWATH model in seaways is larger than that of the single strut counterpart. In addition, a tandem strut SWATH ship needs to have a more structural weight ratio and accordingly bigger displacement compared to a single strut SWATH counterpart for the same payload. Therefore, in conclusion, it can be seen that the powering requirement of a tandem strut SWATH ship is larger than that of a equivalent single strut SWATH ship in calm water and also in seaways alike.

3.2 Zero Speed Motion Responses and Dynamic Loadings

A large number of stationary tests have been performed in order to compare the seakeeping performance of the single and tandem strut SWATH models in head, quartering and beam seas. Some important results are shown herein. Figs. 7 to 16 show the comparison between the computational and experimental results of the motion responses for the SWATH1 and SWATH3 models. The theoretical derivations for the computational method are given in Ref.[13] and this is based on the 3-D linear diffraction theory for the 6 degree of coupled motions of SWATH ships travelling or stationary in waves from an arbitrary heading. The viscous effect on the motions of SWATH ships is also considered in the theory by a semi-empirical method[16].

Since it is expected that the surge response would be maximum in head seas, the surge response of the SWATH1 and SWATH3 models are compared in this heading angle, see Fig. 7. The maximum non-dimensional surge response of the SWATH1 is approximately 1.15 compared to 1.3 for the SWATH3, both of which occur in non-dimensional frequency of about 1.2. In general, it can be seen that the surge responses of the single strut SWATH is larger than that of the twin strut SWATH model. This can be understood by the fact that the surge wave exciting forces of the single strut SWATH is larger than those of the twin strut and that this is coupled with for the two models.

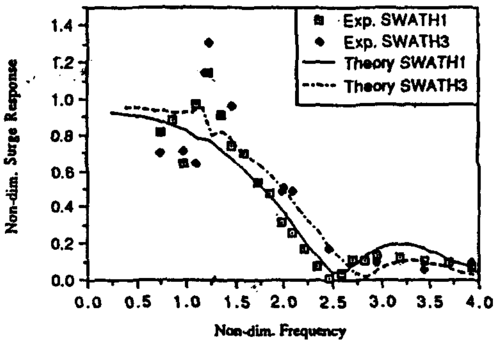

Fig. 7 Surge response in regular head seas

The sway responses of the two models are compared in beam seas. The scattering of the data (see Fig. 8) from the two models shows a similar pattern. The maximum responses at the first peak frequencies due to the coupling effect with the roll motion are nearly the same(non-dimensional the lower drag coefficient of the former compared to the latter resulting in less damping. The theoretical prediction agrees well with experimental results, but, the theory does not show a large response in the vicinity of the peak frequency which seems to occur due to the coupling effect with the pitch resonant. This difference may be caused by a slightly high value of hydrodynamic damping introduced in the prediction. For the present study, a lifting coefficient of 0.07 and drag coefficient of 0.5 are used in each mode of motion value of 0.9) as each other at non-dimensional frequency of 1.2 and 1.8 for the SWATH1 and SWATH3, respectively, despite the larger projected area of the single strut model. This may be due to the blockage effect of the demihull of the single strut on the incoming wave side. This blockage effect can be more clearly seen in comparing the sway responses of the two models in bow quartering seas. The measured sway responses of the single strut model in the bow quartering seas(Fig.9) are larger than those in the beam seas(Fig. 8). This is, however, not the case for the twin strut model(Figs 8 and 10). Therefore, it can be concluded that the maximum side force occurs in quartering seas for the single strut SWATH design but in beam seas for the twin strut design. The second peaks are clear in both cases. In most frequencies, particularly in the supercritical region the theory confirms the experimental results. Low responses from the experiment in the region slightly below the resonance frequency might be brought about mooring stiffness effect on the model motions.

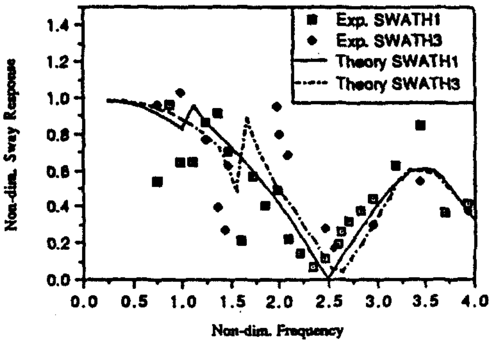

Fig. 8 Sway response in regular beam seas

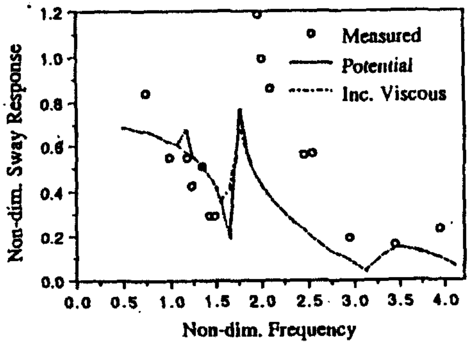

Fig. 9 Sway response of SWATH3 in bow quartering seas

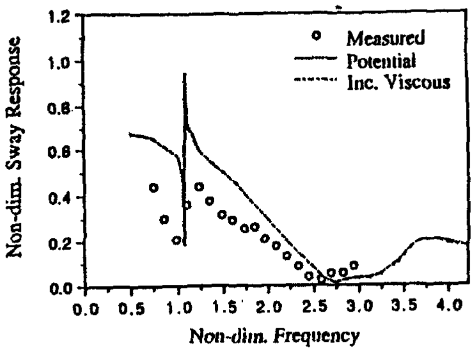

Fig. 10 Sway response of SWATH1 in bow quartering seas

It has been shown that the maximum peak of heave responses for the models is little different in head and beam seas. Fig. 11 shows the comparison of heave response in head seas. Maximum heave response is 1.75 for the SWATH1 compared to 2.4 for the SWATH3. A small discrepancy between experimental and theoretical results occurs only in the subcritical region. In the other frequencies the theory predicts the heave performances of the two models very well. As clearly seen in the figures, the model modification from the tandem to single strut led to a large change in the heave resonance frequency. One of the important results from this design change is that the heave response(including the peak value at the resonance) of the tandem strut model is much smaller than that of the single strut one. The calculated wave exciting forces of the single strut model is higher than those of the tandem strut, as seen in Fig. 12. In addition, the hydrodynamic added mass of the single strut model is much smaller than that of the tandem strut owing to the reduced pressure cancellation effect from the upper surface of the submerged body, see Fig. 13. This results can be found in the same manner with the forward speed, discussed later.

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It has been shown that the maximum roll response occurs in beam seas for both of two models. The non-dimensional roll response of the SWATH1 in beam seas is higher than that of the SWATH3 (Fig. 14). The critical zones of roll responses are near the non-dimensional frequency of 1.0 for the SWATH1 and around 1.5 for the SWATH3. The theory again gives a good agreement with the experimental result for both models. As for the heave responses, a large change in the natural roll frequency can be seen for the two versions. Although it is shown that both the calculated added roll inertia and hydrodynamic damping are higher for the twin strut model, its roll responses are higher than those of the single strut except for the critical region of the single strut model. This can be explained by the fact that the transverse metacentric height of the single version(0.386m) is much higher than that(0.204) of the twin oen, as seen in Table 3, resulting in a higher restoring moment than the twin one. However, if considering the modal periods of most occurring seaways in the coastal area from the operational point of view, the tandem strut SWATH ship would be beneficial compared to the single strut SWATH ship in terms of the roll performance.

The pitch responses of the two models is shown in Fig. 15 for head seas. It has been found that the largest peak occurs in head seas for both of two models. Although the lower waterplane area of the tandem strut seems to be subject to a less pitch exciting moment, its pitch response peak is higher than those of the single strut at the resonant frequency. However, in supercritical zone, the pitch responses of the tandem strut is little different to those of the single, being mostly due to its higher value of longitudinal metacentric height (0.229m) than that (0.207m) of the single strut. As discussed in Ref.[17], for equal waterplane area, increased GM_L will result in a lower ratio of pitch exciting to restoring moment.

The non-dimensional yaw responses of the two model are compared in bow quartering seas. It is shown in Fig. 16 that from the viewpoint of the scattering of the data the two results are not in a good agreement with the predictions. The maximum experimental yaw response of the SWATH1 is roughly one half of the SWATH3. The thoretical predictions exhibit a slight different pattern from the measurement at the low frequencies. However, it can be seen from the theory that the two models do not differ much in terms of yaw motions. It seems necessary to carry out measurements of yaw in different oblique seas in order to confirm the experimental results and to validate theoretical prediction.

Although the main overall dimensions have remained unchanged it is not very convenient to

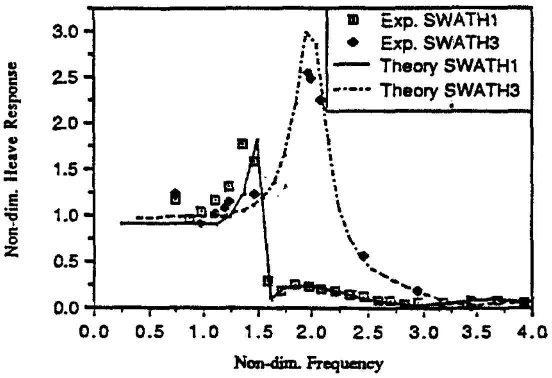

Fig. 11 Heave response in regular head seas

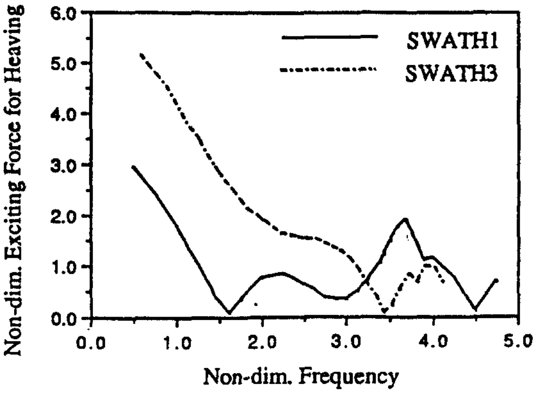

Fig. 12 Heave exciting force coefficient

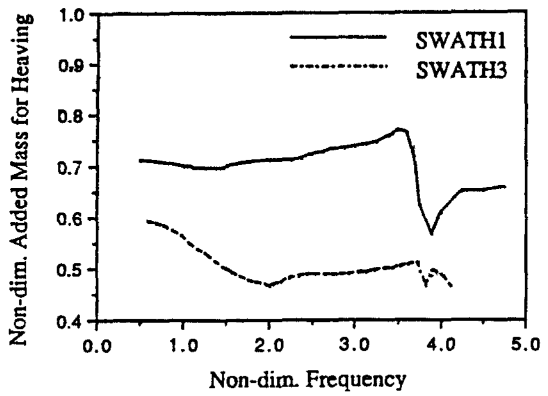

Fig. 13 Heave added mass coefficient

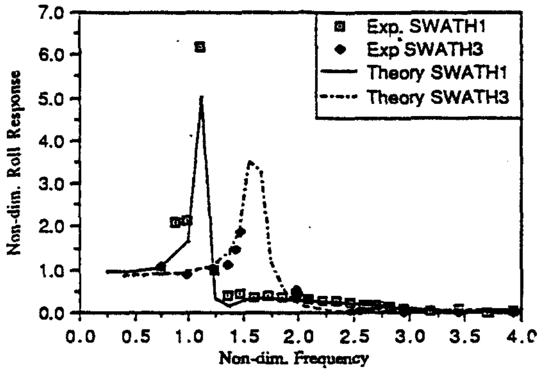

Fig. 14 Roll response in regular beam seas

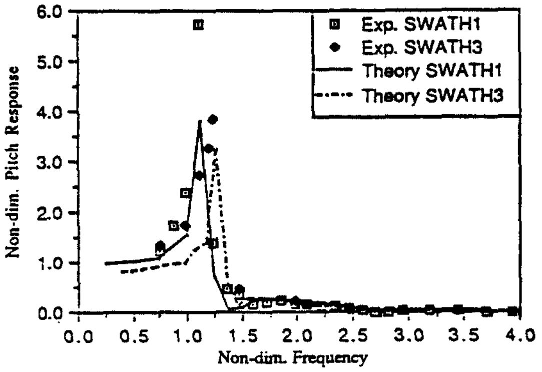

Fig. 15 Pitch response in regular head seas

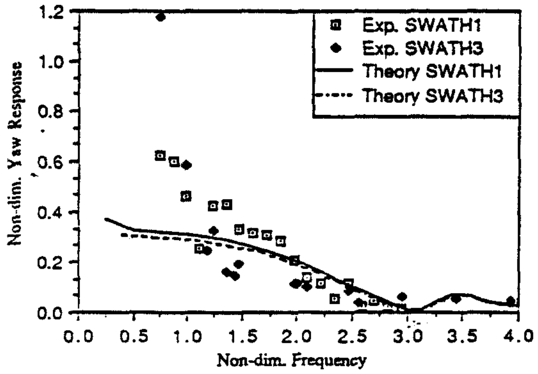

Fig. 16 Yaw response in regular bow quartering seas

compare the bending moment characteristics of the two models directly as the displacements, which is one factor included in the non-dimensionalisation of the bending response, of those models are different. The ratio of the displacement of SWATH1 to SWATH3 is 0.835. Comparing non-dimensional values(Fig. 17), the maximum M_3' of SWATH1 in beam seas is slightly higher, 3.0 compared to 2.65 approximately. However the maximum bending moment per unit wave height is 0.63 KN for SWATH1 compared with 0.679 KN for SWATH3 indicating that the deck of SWATH3 must be the stronger. In quartering seas (Fig. 18), SWATH1 shows a distinctive maximum M_3' associated with the first and second standing waves. The non-dimensional vertical shear force measured is shown in Fig. 19 for the two models. The magnitude of $V3'$ seems to be similar to each other.

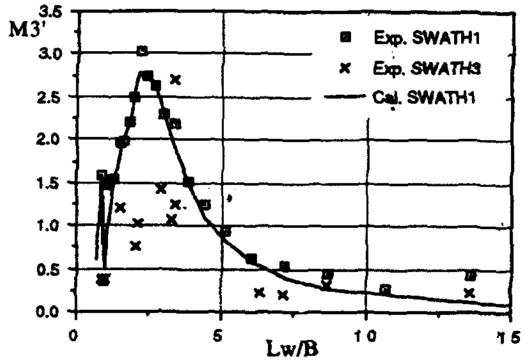

Fig. 17 Non-dimensional bending moment at mid-section of the cross deck in regular beam seas

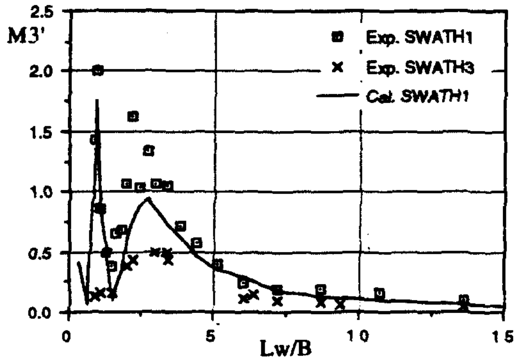

Fig. 18 Non-dimensional bending moment at mid-section of the cross deck in regular quartering seas

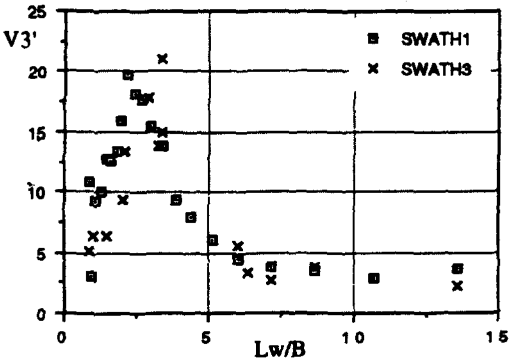

Fig. 19 Non-dimensional vertical shear force at mid-section of the cross deck in regular beam seas

3.3 Forward Speed Motion Responses

If comparing the motion responses between the SWATH1 and SWATH3 in speeds, similar conclusions to those for the stationary condition can be drawn. The heave response of the single strut (Fig. 21) is higher than that of the twin(Fig. 20). The pitch peak value of the single strut SWATH(Fig. 23) is much lower than of the tandem strut one(Fig. 22). As mentioned in section 3.2, the viscous effect shown in the figures is considered by the semi-empirical method. The phenomenon of heave and pitch coupling effect in speeds can be seen in the pitch responses(Figs. 22 and 23), but this seems to be negligible at z ero speed(Fig. 15). It was observed[13] that the magnitude of the coupling effect increases with the increase of the speed. As far as the theory is concerned, it reveals that as speed increases, the large pitch response occurs at heave resonant frequency instead of pitch resonant frequency. The wave 1 and wave 2 shown in Fig. 21 and 23 indicate that wave heights are changed at the fixed wave length in order to investigate into the non-linear motion behaviors of the SWATH model. Except with the resonant region, it was observed

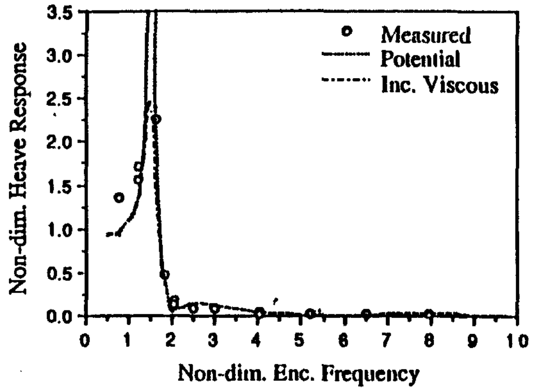

Fig. 20 Heave response of SWATH1 in head seas (Fn=0.26)

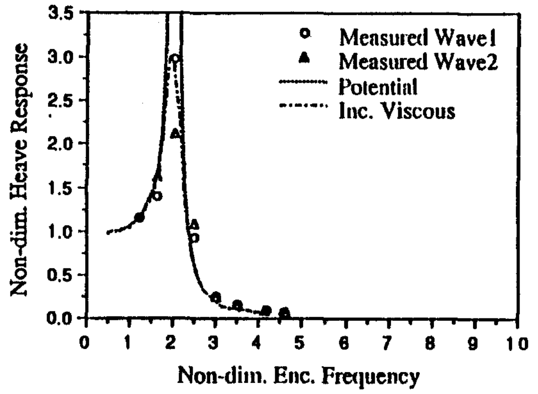

Fig. 21 Heave response of SWATH3 in haed seas (Fn=0.26)

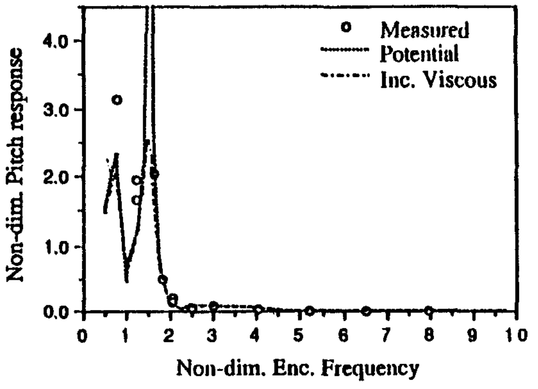

Fig. 22 Pitch response of SWATH1 in haed seas (Fn=0.26)

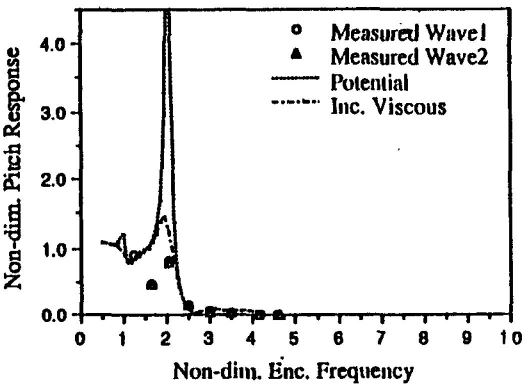

Fig. 23 Pitch response of SWATH3 in haed seas (Fn=0.26)

that the SWATH model responds linearly to the wave height.

3.4 Design Considerations

The motion responses of a surface ship such as heave, pitch and roll can be drawn in a simple manner as a function of the tuning factor, as given in Fig. 24. The tuning factor is the ratio of the natural period of the ship to the period of encounter waves. The largest motion responses occur when the value of the tuning factor becomes unity. For example, according to the experimental results of the SWATH1 and SWATH3 travelling in regular head waves at Fn=0.26, the SWATH1 will experience heave motions around 2.3 times the wave amplitude and the SWATH3 around as

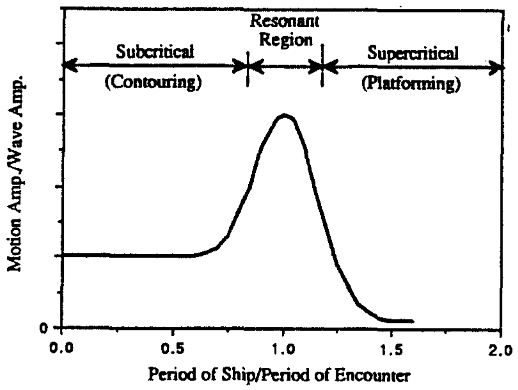

Fig. 24 Typical variation of SWATH motion responses (heave, pitch, roll) vs tuning factor

large as 3 times the wave amplitude(see Figs. 20 and 21). Therefore, the peak value in Fig. 24 depends on the ship as well as on the operational sea condition. As the tuning factor increases, the motion responses become smaller. So, the region beyond the tunning factor of 1.20 is called the supercritical region and the ship runs in a platforming mode in this region. In the subcritical region where the tuning factor is less than 0.75, the ship moves up and down in phase with waves(contouring behaviour) and for example, the heave amplitude as about the same as the wave amplitude, as seen in Figs. 20 and 21.

Therefore, the natural periods of the ship are very important and care should be taken to avoid these coinciding with the modal period of the waves of maximum energy in operating seas to either the supercritical or subcritical region. If the ship can be operated all the time in the supercritical region, this is the best design since her performance and operability are the best in this region. Except for some cases in following seas, this can be achieved by increasing the natural periods of motions of the ship.

The heave natural period of a surface ship is given by the equation:

$$T_{HEAVE}=2\pi\sqrt{\frac{\nabla(1+A_{33}')}{gA_{w\cdot p}}} \tag{1}$$

where $A_{w\cdot p}$ is the waterplane area, A_{33} the heave added mass, $A_{33}'=A_{33}/M$, M the mass of the ship, and ∇ is the displaced volume. The pitch period is given by

$$T_{PITCH}=2\pi\sqrt{\frac{r_P^2+I_{55}'}{g\ GM_L}} \tag{2}$$

where r_P is the pitch gyradius, I_{55} is the pitch inertia and $I_{55}'=I_{55}/M$. The roll period is

$$T_{ROLL}=2\pi\sqrt{\frac{r_R^2+I_{44}'}{g\ GM_T}} \tag{3}$$

where r_R is the roll gyradius, I_{44} the roll inertia and $I_{44}'=I_{44}/M$.

There are two possible ways of increasing the heave period for the fixed displacement: one is to increase the value of A_{33}' and the other is to reduce waterplane area. As seen in Table 3, since the waterplane area of the twin strut SWATH model is much less than that of the single strut SWATH model, the heave natural period of the SWATH1 model is longer that that of the SWATH 3. The limit in reducing waterplane area is decided by the static roll stability requirement as well as by structural and access considerations. As explained in Ref.[18], 50 percent reduction in waterplane area requires 41.4 percent increase in hull spacing to maintain the optimum roll static stability. In practice, too much increase in hull spacing is undesirable. The heave added mass of a SWATH can be increased using hulls whose horizontal axis is greater than the vertical axis (non-circular hull). The introduction of fins also increases the heave added mass value.

The pitch period can be increased by either increasing the longitudinal mass inertia or reducing GM_L. The longitudinal mass inertia(pitch gyradius) can be increased by distributing mass near the ends of the SWATH. This is illustrated, in Table 3, in that the longitudinal mass inertia of the tandem strut SWATH1 is much larger than that of the single strut SWATH3. However, there is little difference in the pitch periods of the two design due to the much increased GM_L of the SWATH1 compared to the SWATH3. As discussed in the previous section, this increased GM_L contributes to reducing the pitch motion due to the increased restoring moment. In general, a shorter strut and longer hull combination provides a longer pitch period with the help of the decreased GM_L. Also, fins attached to the hulls increase the pitch period. In general, one pair of fins produces more than 10 percent increase in pitch period compared to the bare hull.

In general, a wider hull spacing results in a greater roll inertia and hence, provides a long roll natural period. A smaller GM_T gives a long natural period, as seen with the SWATH1, but this lower GM_T results in higher roll responses than those of the SWATH3 due to its much reduced restoring moment. Because of the twin hull concept of the SWATH, a long natural period of roll can be easily guaranteed while providing a relatively high GM_T.

4. Conclusions

The two SWATH models mentioned in this paper is not scaled from a full scale ship for a specific role design but built for the research purpose, mainly, for the investigation of the calm water resistance. Therefore, the design of each ship can be made to improve her performance for a specific role in an operating sea condition, respectively. However, a comparative study between the two models seems to be valuable and some conclusions drawn based on this paper can be utilized in the design of SWATH ships.

The frictional resistance component of a SWATH ship is larger than the residuary resistance, which is the characteristics of the SWATH design. A tandem strut SWATH ship has a more wetted area than that of a single strut SWATH ship having the same displacement as each other. In addition, a tandem strut SWATH ship needs to have a more structural weight ratio and accordingly bigger displacement compared to a single strut SWATH counterpart for the same payload. Therefore, it can be said that the powering requirement of a tandem strut SWATH ship is much larger than that of a equivalent single strut SWATH ship having the same payload as each other.

Owing to the blockage effect, the measured sway responses of the single strut model in the bow quartering seas are larger than those in the beam seas. This is, however, not the case for the twin strut model. Therefore, it can be said that the maxiumum side force occurs in quartering seas for the single strut SWATH design but in beam seas for the twin strut design. In addition, the magnitude of the side force in quartering seas for the single strut SWATH ship is larger than that of the tandem strut design in beam seas.

The heave response of a tandem strut SWATH design is much less than that of a single strut SWATH one due to its much smaller waterplane area as well as larger added mass. If considering the modal periods of most occurring seaways from the operational point of view, the tandem strut SWATH ship would be beneficial compared to the single strut SWATH ship in terms of the roll performance, but of little difference in the pitch responses for the two models.

The bending moment of a single strut SWATH ship seems to be larger than that of a tandem strut SWATH design. Therefore, the deck of a single strut SWATH ship would be required to be stronger compared to a equivalent tandem strut SWATH one. In addition, the maximum bending moment value with the single strut SWATH ship occurs at the frequency where the first standing waves are observed in between the two demihulls.

In addition to the points made above, as indicated in the introduction, a single strut SWATH ship has various practical beneficial aspects compared to a tandem strut SWATH design such as simplicity of design, better accessibility to the lower hulls for maintenance, greater structural strength, larger payload capacity, greater static stability and higher TPC etc.

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