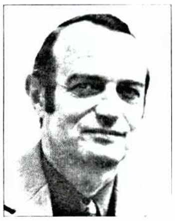

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The enhancement of seakeeping qualities of fast catamaran by means of stabilizing foils

SUMMARY

Some aspects of insufficient seakeeping qualities of fast catamarans are commonly known. The intention of this investigation was to obtain quantitative data about the influence of application of hydrofoils on seakeeping qualities of a fast catamaran. Two types of foils were investigated: single foil spread between the hulls and double T - foils under the bows. Three locations of a single foil over the ship length and three angles of attack were tested.

The comparison was made between resistance, accelerations, heave and pitch in irregular head waves of the ship with and without foils. Quantitative effects of foils in different configurations and different sea and operation conditions were estimated.

INTRODUCTION

The fast catamarans able to reach 30÷50 knots have dominated passenger-ferry shipping on short and middle distances the during last fifteen years. Trends to apply them in cargo trade are also observed today.

The seakeeping qualities of the ships are rather not good due to their very slender hull form - specially as far as high accelarations in head and oblique waves are concerned. Damping abilities of hydrofoils located under or between the catamaran hulls are already recognized, quantitative data useful for desingers are still lacking.

At present two main types of stabilizing foils applicable to catamarans are the following :

- ❖ foils with automatically controlled angle of attack (ride control system), relatively complicated and expensive
- ❖ fixed foils, technologically simple and cheap, but not so effective as the first type.

Foils of the second type are the object of this investigation carried out within the framework of a research project financed by The State Committee for Scientific Research.

Two types of fixed foils were tested :

- ➢ a single foil extended between the hulls and
- ➢ two smaller T - foils located under the bows of both hulls.

Influence of two main parameters was investigated :

- ✦ the location of the single foil over the ship's length and
- ✦ the angle of incidence (for the single foil only).

The seakeeping qualities are expressed by the following reactions of the ship on wave excitations :

- vertical accelerations at the bow and at LCB
- heave and pitch
- added resistance in waves.

The stabilizing effect of the foil is expressed by the ratio of a given reaction of the ship with foil to the relevant reaction of the ship without foil. There is no universal index of seakeeping qualities so far, therefore all the characteristics were compared separately.

GEOMETRICAL CHARACTERISTICS OF TESTED SHIP AND FOILS

The investigations of influence of the stabilizing foil on seakeeping qualities of the catamaran were conducted with the model F of the fast catamaran hull shown in Fig.1. and of the main particulars given in Tab.1.

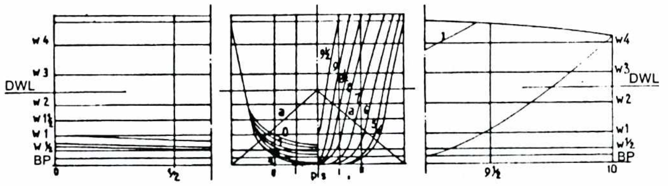

Fig.1. Hull form of the tested ship

Tab.1. Main particulars of the tested catamaran F

Main particulars			Value
Length at DWL	L_{ws}	[m]	38.59
Breadth of one hull	B_{Hs}	[m]	2.385
Draught	T_s	[m]	1.197
Block coefficient	C_B	[-]	0.581
Displacement	∇	[m^3]	128.200
$L_{ws}/(\nabla/2)^{1/3}$	-	[-]	9.640
Dist.of planes of symmetry	B_{Ss}	[m]	9.250
LCB from station 0	$x_v\ /L_w$	[%]	40.100
Longitudinal radius of inertia	k_{yy}	[-]	0.288

The single foil was installed between the hulls as shown in Fig.2. It was fixed onto two vertical struts to simplify changing its location and angles of attack. The tested positions F_1, F_2, and F_3 are shown in the same figure.

Double bow foils of type ⊥ are shown in Fig.2 (version F_4). Their span was so selected as not to exceed the breadth of ship's hull, and their area was smaller than that of the single foil. All foils and struts were made of the same asymmetrical circular profile of the relative thickness equal to 0.06.

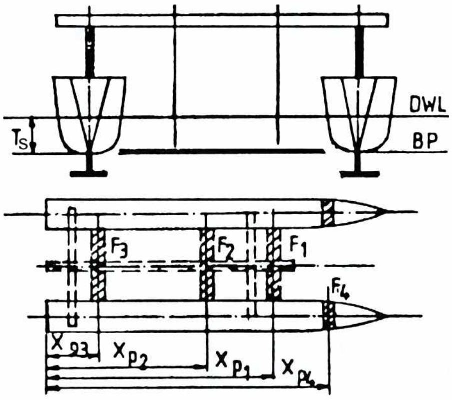

Fig.2. Location of foils on the model

Two models described in the next chapter were tested.

For some technical reasons the dimensions of the small model foil were different from these of the large model foil. The main particulars of the full-scale foils are given in Tab.2.

Tab.2. Dimensions of the full-scale foils

Foil type	Span L [m]	Chord C [m]	Area S [m]	Aspect ratio [-]
Single foil Small model	6.50	0.75	4.87	8.67
Single foil Large model	5.32	0.76	4.04	7.00
Double foil ⊥ Small model	1.675	0.75	1.25	2.24

The parameters of the foils which were variable during the tests are given in Tab.3.

DOMAIN OF INVESTIGATIONS AND RESULT PRESENTATION FORMS

The model tests were conducted in two stages and in two towing tanks. The first stage of investigations was carried out in the small tank (of 30 x 3 x 1.5 m) at the Technical University of Gdańsk. The tests were conducted in calm water and in regular head waves to find an optimum location of the single foil over the ship length (at F_1, F_2 or F_3 location) and additionally to estimate the respective effect of the double foils ⊥ located under the ship bows. The tests were conducted at the scale 1:25. The second stage of the research aiming to find the influence of the angle of attack on the foil-induced stabilizing effect was conducted in the large tank (of 240 x 12 x 6 m) of the Ship Design and Research Centre, Gdańsk, with the use of a 1:9.5 scale model, since in this case measurement exactness was required larger for the reason of smaller differences of the measured values. It was also possible to check the behaviour of the model in the irregular waves which could be directly generated in the tank for a given wave spectrum. The investigations conducted in the small tank by using the hull without foils and that with the foils of all configurations, consisted of the following tests :

- **in calm water :**
  measurements of the resistance R_T, trim θ_0 and emergence z_0 in the speed range of 12÷40 knots ($0.3 < Fn < 1.05$)
- **in 6 regular head waves :**
  measurements of the resistance R_{TW}, pitch θ, heave z and vertical accelerations at FP and at CG; the wave parameters were changed within the following ranges :

$$\begin{array}{lllll}
0.7 & < & \omega_s & < & 1.7 \quad [\mathrm{s/rad}] \\
3.26 & > & \lambda_s/L_{ws} & > & 0.55 \quad [-] \\
9.0 & > & T_s & > & 3.7 \quad [\mathrm{s}] \\
 & & 2\zeta_A & \approx & 1.0 \quad [\mathrm{m}]
\end{array}$$

All the tests were performed at five ship speeds : ($0.385 < Fn < 0.9$).

The investigations in the large tank were conducted by using the hull without foil and with the single foil situated in the bow position F_1 at three angles of attack in calm water and in the waves of the same parameters as given above, but at two ship speeds only (Fn= =0.53 and 0.9). Additionally, two tests in irregular head waves were made. The wave spectrum was modelled according to the ISSC standard for $T_1 = 4.9$ s, $H_{1/3} = 1.135$ m and the ship speed of 20 and 34 knots. Direct test results [1,2,3] were presented in the form of the response amplitude operators (RAOs) :

$$a_A/g/\zeta_A(\omega),\ \ \theta_A/\zeta_A(\omega),\ \text{and}\ z_A/\zeta_A(\omega)\ \text{respectively, at}\ Fn = \text{const.}$$

Then they were transformed to the form of the characteristics in irregular waves by means of the common method based on the superposition principle and ISSC wave spectrum. The characteristics were originally presented in the form of the relative variances of the particular responses to wave excitations where the relative variance equals :

$$\overline{m}_{oi}(T_1) = \frac{m_{oi}(H_{1/3}, T_1)}{H_{1/3}^2} \tag{1}$$

and

$$m_{oi} = \int_0^\infty |RAO(\omega)|^2\, S(\omega) d\omega \tag{2}$$

Tab.3. Variable parameters of the foils

Foil type	Foil location x_{pi} / L_{ws}			Foil angle of attack α_i [°]		
Single foil Small model (in the scale 1:25)	F_1 0.648	F_2 0.412	F_3 0.071	F_1 + 2.5	F_2 + 2.5	F_3 + 2.5
Single foil Large model (in the scale 1:9.5)	F_{50} 0.648	-	-	F_{51} + 3.1	F_{52} + 1.3	F_{53} - 0.8
Double foil ⊥ Small model	F_4 0.872	-	-	F_4 + 2.8	-	-

F_{5i} - *Large model, different angles of attack*
F_{5o} - *Large model without foil*

The added resistance in waves is expressed by the nondimensional coefficient r^*_{AW} :

$$r^*_{AV}(T_1) = \frac{\overline{R}_{AW}(H_{1/3}, T_1)}{2\rho g L_{ws} H^2_{1/3}} \qquad (3)$$

Values of the relative increments of the variances $\overline{m}_0$ for a given foil combination related to respective values for the hull without foils, were calculated for each of the characteristics (acceleration, heave, pitch) separately to compare seakeeping qualities of a catamaran with foils and without them. The applied measure of quality is defined by the following expression :

$$\Delta\overline{m}_{0i} = \frac{\overline{m}_{0i} - \overline{m}_{00}}{\overline{m}_{00}} 100[\%] \qquad (4)$$

Knowing the Δm_{0i} one can easily find the relation of particular significant response amplitudes by using the formula (5) :

$$\frac{X_{Ai}}{X_{A0}} = \sqrt{\frac{\overline{m}_{0i}}{\overline{m}_{00}}} = \sqrt{1 + \Delta\overline{m}_{0i}} \qquad (5)$$

The increments of added resistance can be presented as follows :

$$\Delta r^*_{AW} = \frac{r^*_{AWi} - r^*_{AW0}}{r^*_{AW0}} 100[\%] \qquad (6)$$

Comparing the particular characteristics of seakeeping qualities is difficult because their maxima occur at different speeds and frequencies. Therefore it was decided to compare the relative increments of particular variances $\Delta\overline{m}_{0i}$ for four combinations of operational conditions :

- maximum values out of the entire tested area
- maximum values at the speed of 34 knots (Fn = 0.9, at different frequencies)
- the values at Fn = 0.9 and $T_1 = 4.4$ s
- the values at the speed of 20 knots (Fn = 0.51) and $T_1 = 4.4$ s

The period $T_1 = 4.4$ s was chosen as typical for the Baltic waves at the wind speed of 6°B ($H_{1/3} \approx 1.2$ m).

RESULTS OF THE INVESTIGATIONS

When the model tests were completed it appeared that not all parameters of the motion were consistent for the tests in the two towing tanks. The repeatability of results was quite good for the resistance of the hull without foils, but motions in waves in the small tank were smaller. It was caused partly by the scale effect, but also due to the effect of the different model towing methods applied in the two cases. In the small tank the point of towing force was applied above the model deck, and in the large tank - at the height of the shaft line. For this reason the sets of results obtained from the tests in each of the tanks must be compared within themselves, separately from each other.

Resistance in calm water

The comparison of the resistance in calm water is interesting because it shows directly the influence of the foil location and its angle of attack on the resistance. The increments of the total resistance for all foil combinations are given in Tab.4. The positions F_1 and F_2 are almost equivalent from this point of view and the position F_3 is clearly the worst. At these foil parameters its lift force was too small to make the hull resistance decrease. The fully free model F_{50} in the large tank gave quite reliable results and showed that the resistance increments in the case of the foil posed at the bow (F_{51}) are small and even negative at high speed.

Therefore the foil should be located at the bow part of the ship as far as the resistance increment is concerned.

Influence of foil location on seakeeping characteristics

The influence of the foil location on particular seakeeping characteristics in irregular seas is shown in Fig.3.

Additionally the effect of the double T - foils is presented in the same figure. All the foil positions F_1, F_2, F_3 and F_4 were tested at the same angle of attack.

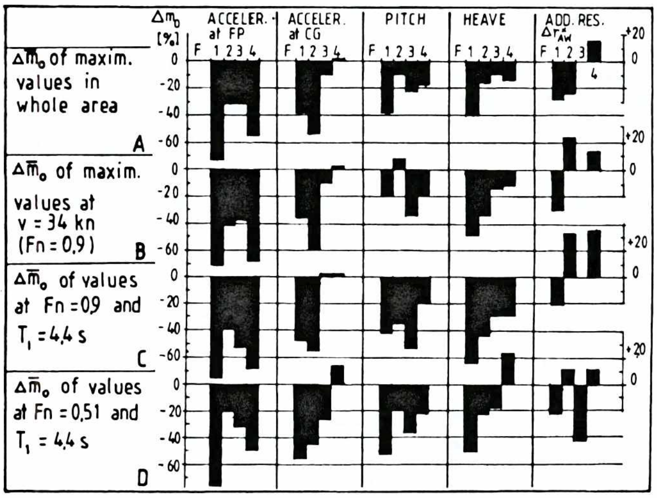

Fig.3 Relative increments of variances of ship responses to irregular waves at different foil locations ($F_1 \div F_4$)

Tab.4 Relative increments of the total resistance in calm water

V [kn]	20	25	30	34	40
R_{T0} (F_0=F_{50}) [kN]	68.7	83.8	102.1	121.0	162.4
$\Delta R_T = [(R_{Ti} - R_{T0})/R_{T0}] \cdot 100[\%]$					
F_1	18.0	10.0	17.5	19.0	10.8
F_2	16.4	11.0	17.5	18.5	11.0
F_3	30.3	24.7	27.3	28.1	19.1
F_{51}	7.6	7.2	5.6	3.6	- 2.2
F_{52}	7.4	6.7	5.1	2.9	- 5.7
F_{53}	9.1	9.3	8.9	8.4	4.6
F_4	16.4	9.5	12.6	15.7	11.4

The following observations can be made :

- the highest damping of the accelerations at FP is obtained at the foil location F_1; with the decrease of variances $\Delta\overline{m}_0 \approx 75\%$ and the decrease of amplitudes $\Delta a_{AF} \approx 50\%$
- the foil location F_2 is the best one in view of the accelerations at CG : with $\Delta\overline{m}_0 \approx 50\%$, $\Delta a_{AG} \approx 25 \div 40\%$; however, the damping at the foil position F_1 is not much worse and even better at lower speeds
- the foil location F_2 is the worst in view of the pitch motion, in some cases the foil placed at the bow is the most favourable (A, D), in others - the foil placed at the stern (B, C)
- the foil position F_1 is the best on the account of the heave, with $0.4 < \Delta\overline{m}_0 < 0.65$, $\Delta z_A \approx 20 \div 40\%$ in all the cases
- decrease of the added resistance in waves can be obtained at the foil location F_1 only: with the negative value of $\Delta r^*_{AW} \approx 20 \div 30\%$; position F_3 influences the added resistance minimally.

It is evident that the effects at other angles of attack can be different.

Influence of foil angle of attack on seakeeping characteristics

The effect of single-foil angle of attack was investigated for the three angles given in Tab.3. The range of the angle variation was limited because its higher values ($\alpha_1 > 3°$) caused too large trim in calm water and smaller angles ($\alpha_1 < -1°$) made the trim negative.

The test results transformed to irregular sea, presented in the form of the relative increments of variances of particular ship responses related to those of the ship without foil are shown in Fig.4.

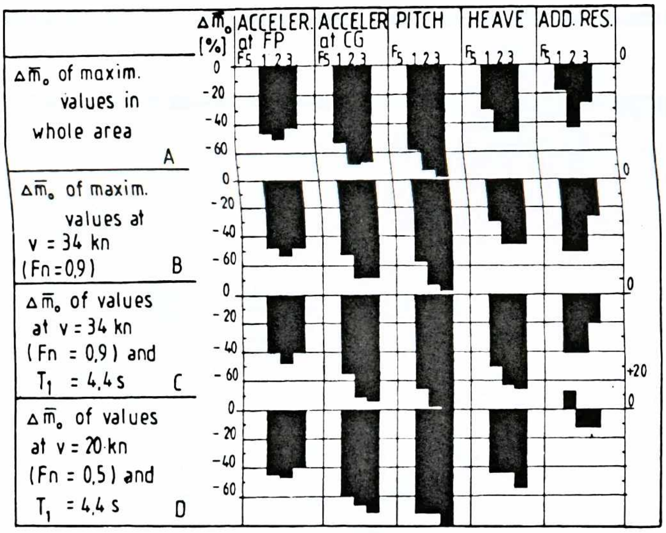

***Fig.4** Relative increments of variances of ship responses to irregular waves at different foil angles of attack*

In general, the influence of the angle of attack on seakeeping characteristics can be deemed not significant.

In particular :

- accelerations at the bow are damped practically to the same extent at all angles from the range -1° to +3°
- damping of accelerations at CG, of heave and pitch as well, grows when α_i diminishes
- the lowest increments of added resistance in waves occur at small angles of attack
- the observed influence of the angle of attack on the ship motions is not dependent on the ship speed.

OTHER REMARKS

The presented investigations gave an opportunity to make some other observations. Two of them seem to be important.

The first is the influence of the longitudinal mass moment of inertia on ship seakeeping characteristics. Model F was tested in waves with two radii of inertia: $\rho_1 = 0.25$ and $\rho_2 = 0.296$. In general, the version with ρ_2 shows better seakeeping qualities than that with ρ_1. The lower sea state and the higher ship speed the higher its predominance as far as the resistance and pitching is concerned. Regarding the accelerations and heaving, the version with ρ_2 is more favourable in the speed range of $0.5 < Fn < 0.8$ and wave period of $3.5\ s < T_1 < 5.5\ s$. In general, the higher ship speed and wave length the smaller the effect of moment of inertia on seakeeping characteristics.

Secondly, the results of the tests in regular waves, transformed to irregular ones by means of RAOs, were compared with those obtained in the direct trials in irregular waves. The results of the comparison are given in Tab.5 in the form of the relative differences of the values of the motion characteristic parameter amplitudes obtained in both cases.

***Tab.5.** Comparison of the test results in regular and irregular waves [%]*

V[kn]	Δz_A	$\Delta\theta_A$	Δa_A(FP)	Δa_A (CG)
20	+ 4.7	- 7.3	- 8.0	- 9.7
34	- 4.4	- 17.7	-11.0	-13.3

The sign (-) means that the values obtained directly from the tests in irregular waves are greater than those from the tests in regular waves. The differences could be explained by the approximations introduced in the transformation method and inaccuracies in wave spectrum simulation in the towing tank. It is interesting that practically all the differences are negative.

CONCLUSIONS

The investigation results can be concluded as follows :

⇒ the fixed foil spread between the hulls of a catamaran, can be an effective tool for damping vertical accelerations and ship motions in waves

⇒ the most efficient location of such foil upon the ship length is that at its bow part, between LCB and 0.75 L_{ws} station

⇒ the foil angle of attack has rather small influence on its damping effectiveness; the angle $\alpha_i = 0$ seems to be the best

⇒ the double ⊥ foils, even of twice smaller area than that of the single foil, are of almost the same effectiveness of damping the vertical accelerations at the bow; however, their damping effect on other seakeeping characteristics is much smaller.

Acknowledgments

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NOMENCLATURE

a_A - amplitude of acceleration [a/g, m/s²]
a_{AF} - amplitude of acceleration at fore perpendicular
a_{AG} - amplitude of acceleration at the centre of gravity (or at LCB)
Fn - Froude number [-]
g - acceleration of gravity [m/s²]
h - height of regular wave [m]
$H_{1/3}$ - significant wave height [m]
m_0 - variance of the process of a given reaction
r^*_{AW} - nondimensional coefficient of added resistance in waves
R_T - total resistance in calm water [kN]
R_{AW} - mean added resistance in waves [kN]
R_{TW} - total resistance in waves [kN]
RAO - response amplitude operator, RAO=X_A/ζ_A
s - lower index related to the full scale
T_1 - characteristic period of oscillation [s]
V - ship speed [m/s, kn]
X_A - generally: oscillation amplitude
z - heave or emergence
z_A - heave amplitude [m]
α_i - hydrodynamic foil angle of attack [deg]
ζ_A - wave amplitude [m]
θ - pitch or trim
θ_A - pitch amplitude [deg]
λ - wave length [m]
ρ - water density
ω - oscillation frequency [rad/s]

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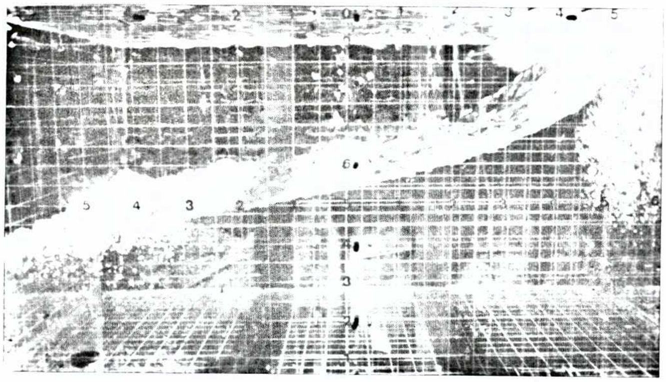

Instantaneous location of the fluid free surface resulting from tank model's motion (Jlustration to the current report on page 14)