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Hydrodynamic characteristics of fast cargo ships of new generation

SUMMARY

The paper contains results of investigations on the design of three types of fast container ships: catamaran, semi-trimaran and monohull whose resistance, seakeeping qualities and propulsive characteristics were tested. Influence of some parameters of the ships on their resistance was also considered. Comparison of their characteristics with those of traditional hull forms showed that the new designs appeared superior especially with respect to ship resistance.

INTRODUCTION

Last decade brought rapid development of fast maritime transport in the domain of passenger-car ferry operation, manifested mostly in dynamic increase of the number of fast catamaran ferries, but also in growing speed of monohull ferries, whose average speed became stabilized on the level of 40 knots in the beginning of the 1990s and has kept increasing slowly.

Since mid-1990s the tendency has been observed also in cargo ships (ro-ro ships, containerships etc). The fact was confirmed by many publications and discussions during international conferences as well as by large international and national research projects carried out on that topic.

In the area of trans-European transport the main arguments for sea transport are over-crowded highways ; it is possible to replace car and railway transport on many routes by the maritime one. It mostly concerns routes leading from the continent to Great Britain, Ireland, Scandinavia and in the region of the Mediterranean Sea. To make it profitable it is sufficient to increase sea transport speed to 30÷35 knots, i.e. that equivalent to the speed of railway and car transport [2,5,6,4]. Energy consumption of ship transport equals to 1/5 of that of cargo car transport, and to 1/20 of that of air transport.

Having the speed twice higher, one can use twice smaller number of ships to carry the same amount of cargo on the same distance in the same time. According to Levander [6] greater costs caused by higher speed of ships would be compensated by „the value of time". The final cost of fast sea transport, especially on short distances (to about 600 n.m) would not be drastically higher than that of traditional ro-ro ships. There is a dominant opinion that at first small fast feederships will be demanded and then larger transoceanic express vessels (of load carrying capacity > 10 000 t) [4]. Such fast cargo ships must have not only low-resistance forms and high propulsive efficiency, but also present good seakeeping qualities to be more independent of weather conditions.

CTO RESEARCH PROJECT ON „FAST CARGO SHIPS OF NEW GENERATION"

Going to meet the future demands of shipowners, CTO realized the research project (No 9T12C07414, financed by The State Committee for Scientific Research) aiming at elaboration a fast cargo ship form of very low resistance and good seakeeping qualities. Such hull could be the basis for design of a container feeder or ro-ro ship or another vessel of the kind. The volumetric displacement of 4200 m^3 assumed for this ship provides about 1500 dwt load carrying capacity, i.e. payload of about 100 TEU or 55 trailers [9]. In the first stage of the investigations two basic solutions were selected : catamaran and monohull. The catamarans gained wide popularity as ferry-ships due to their excellent stability and large deck area which make them very useful for such aims. The monohulls could be better from the resistance point of view but they would form some stability problems. A trimaran hull was also considered, but it was finally rejected as the design whose realization was not very probable in the near future.

Model tests of the selected designs were carried out in calm water and in irregular waves in a wide range of ship speed. Results of the investigations are presented in this paper in comparison with characteristics of existing ships having traditional hull forms.

The comparisons show that the assumed proportions and hull forms are suitable for the considered speed range of 30÷35 knots, and they can be the basis for designing a family of future fast cargo ships. Two types of propulsors for the investigated ships were also tested:

traditional screw propellers and podded propulsors. The influence of main hull form parameters on hydrodynamic characteristics of the ships was investigated in a limited range only.

HULL FORM CHARACTERISTICS OF FAST MERCHANT SHIPS

The significant increase of speed of modern ferries and passenger ships caused essential changes in dimensional proportions of their hulls in relation to the traditional merchant ships of 20÷22 kn service speed.

The traditional fast cargo ships are of the following main proportions :

$$L_W / \nabla^{1/3} \approx 5.5 \div 6.7 \qquad L_W / B_W \approx 6 \div 7 \qquad c_B \approx 0.6 \div 0.7$$

New designed fast ships of new generation (of speed over 27kn) are characterized by larger slenderness, much smaller block coefficient and larger deadrise angle.

Fast catamarans are of exceptionally slender hulls with the following proportions [9] :

$$L_W / \nabla^{1/3} > 8 \qquad L_W / B_W \approx 14 \div 20$$

$$B_W / d \approx 1.5 \qquad c_B \approx 0.45 \div 0.6$$

Fast monohulls are distinguished also with the high slenderness coefficient $L_W / \nabla^{1/3} > 8$, but their L_W/B ratio increases not so much because of stability demands. The hull proportions make these ships similar to frigates and destroyers. Available model tests show that the $L_W / \nabla^{1/3}$ coefficient has decisive influence on resistance of fast ships. The effect of changes of L_W/B and B/d ratios upon resistance is not clear at the moment. The published data for fast monohulls show their very low block coefficients in the range of 0.35÷0.45. Probably the high slenderness coefficients $L_W / \nabla^{1/3}$ (not only the relationship between resistance and c_B) make the c_B values low.

The published model test results of HSC (high speed craft) are too scanty and incomplete to determine the quantitative influence of those parameters on hull resistance.

The presented investigations are hoped to be helpful in filling the gap a little.

The basic hull forms (of catamaran and monohull) for fast containership (or ro-ro ship) were designed by CTO research team with taking into account the above mentioned indications and CTO's own experience.

The catamaran was tested in two versions: the first with the relative hull distance $B_S/L_W = 0.207$ (M 523 model), and the other with $B_S/L_W = 0.25$ (M 523-A model). A single hull of it was also tested to determine the interference factor F_{IR}.

Three monohull models : M 517, M 536 and M 536-A were tested of the same displacement, length and slenderness coefficient $L_W / \nabla^{1/3}$. M 517 and M 536 models differed from each other only with values of the L_W/B and B_W/d ratios. Both of them had a small cylindrical bulb at the bow. The M 536-A model was essentially the same as M 536, but it got a simple vertical bow (without any bulb). All the hull forms were characterized by rather large deadrise angle of ~ 20°. The hull form characteristics of the main considered ships are given in Tab.1. and their basic hull forms are shown in Fig.1.

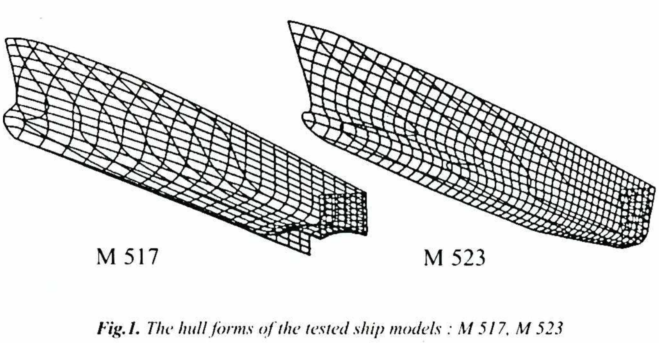

Fig.1. The hull forms of the tested ship models : M 517, M 523

The catamaran was designed for waterjet propulsion, and the monohull - for classic screw propulsion with naked shafts, or for podded propulsors.

***Tab.1.** Hull form characteristics of the tested ship models (full scale ship dimensions)*

Dimension		Catamaran	Monohulls	
		M 523	M 517	M 536
L_W	[m]	120.00	135.25	135.25
∇	[m³]	4200	4200	4200
$L_W/\nabla^{1/3}$	[-]	9.37	8.38	8.38
L_W/B	[-]	16.00	9.00	8.00
B/d	[-]	1.53	3.32	4.14
c_B	[-]	0.476	0.456	0.460

A semi-trimaran (M 555 model) was also tested. It was based on the M 517 hull with two sponsons located symmetrically at the stern. The length of the sponson was 0.3 L_W and its L/B = 26.67. The displacement of both sponsons amounted to 9% of the total one.

RESISTANCE CHARACTERISTICS IN CALM WATER

To estimate the quality of the designed hull forms total resistance values of the tested hull forms were compared with the best of them and that of the traditional ship hull forms. For convenience the resistance is presented in function of ship speed (and not of Froude number). The length of all ships (except of the catamaran) was assumed the same then these arguments are synonymous.

In Tab.2 the relative differences are presented of the resistance of particular hull forms and that of M 517 mother version [8].

$$\Delta R_{TS} = \frac{R_{TSi} - R_{TS517}}{R_{TS517}} \; [\%]$$

***Tab.2.** Relative resistance of the tested hulls (versus full scale speed)*

V[kn]	ΔR_{TS}				
	M 523	M 523-A	M 536	M 536-A	M 555
20	+82	+86	- 4.0	- 1.4	+67.3
25	+81	+72	- 0.5	+1.8	+56.4
30	+64	+60	- 0.2	+2.0	+37.4
33	+49	+42	+1.4	+4.8	+37.5
35	+32	+25	- 3.7	- 0.4	+27.9
40	+23	+18	+3.0	+6.2	+30.4

The resistance of the catamaran (M 523, M 523-A in Tab.2.) significantly exceeds that of the slender monohulls (M 536, M 536A). At the assumed speed of 33 kn the difference is 42÷49% in relation to the most slender form (M 517). Probably, at the speed of 45÷50 kn the resistance of the catamaran would be equal to that of the monohull. The increase of the distance between catamaran's hulls from $B_S/L_W = 0.207$ to $B_S/L_W = 0.25$ brought the decrease of resistance by about 5%. The interference factor F_{IR} decreased from 1.18 to 1.13.

According to Miller-Graf [10] the average value of the factor for fast catamarans at $F_n = 0.5$ (i.e. here at 33 kn) amounts to 1.4. The resistance values of the three tested monohull versions insignificantly differ only at higher speeds (above 30 kn). The hull form without any bulb (M 536-A) is of about 4% smaller resistance than the same with the bulb (M 536). It is interesting that the forms M 517 and M 536, having the same $L_W / \nabla^{1/3}$ and c_B, but different L_W/B and B_W/d, experienced practically the same resistance, and only at above 35 kn speed the form of the higher L_W/B is slightly better. Semi-trimaran's resistance appeared to be about 37% greater than that of the monohull at 33 kn speed. There are some indications in the literature that a gain in resistance could be achieved only at L_W/B=15÷20 of the main hull. However such solution is not acceptable for other reasons. Therefore further investigations on that hull form were stopped.

It is difficult to compare resistance qualities of the designed hull forms with those of the traditional ones because of almost complete lack of published data for their resistance at so high speeds.

The traditional cargo ships of the speed of up to 18÷22 kn. ($F_n \sim 0.3$) are considerably larger than the investigated ones, therefore after reduction of their dimensions (on the principle of geometrical similarity) to the displacement $\nabla = 4200\ m^3$ the range of obtainable data covered only a part of the investigated speed range as Froude number of the investigated ships was about 0.5. Hence the following four ships : M 516-B, M 458-F, M 493 and M 529 tested at CTO in a higher range of speed were chosen for comparison.Two first of them are containerships, M 493 is a frigate and M 529 is a new container carrier designed for 27 kn speed. Geometrical characteristics of the ships recalculated to 4200 m^3 displacement are given in Tab.3 and their resistance is presented in Fig.2 in the form of the relative resistance coefficient $\varepsilon = R_T / \Delta g$.

Tab.3. Geometrical characteristics of the compared ships

Row	Dimension	M 458 F	M 516 B	M 493	M 529	M 536
1.	L_w [m]	97.9	118.4	80.35	124.06	135.25
2.	∇ [m^3]	4200	4200	4200	4200	4200
3.	$L_w / \nabla^{1/3}$ [-]	6.09	6.76	7.00	7.69	8.38
4.	L_w / B [-]	6.46	7.05	7.32	8.12	8.00
5.	B_w / d [-]	3.24	4.29	3.27	3.61	4.14
6.	c_B [-]	0.613	0.71	0.516	0.524	0.460
7.	Original ∇ [m^3]	27 083	10 495	1520	15 270	4200
8.	Resistance at 30 kn speed [kN]	> 2500	1840	1670	1400	952

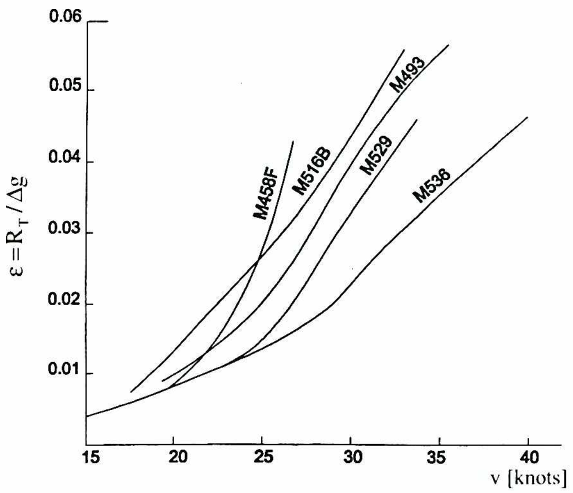

Fig.2. Relative resistance coefficients of the compared ships versus speed

In Tab.3 (row no.7) the original displacement values of particular ships are shown. In row no.8 the resistance of particular hull forms at 30 kn speed, recalculated to 4200 m^3 displacement is presented. From Fig.2. it can be observed that the resistance of M 536 ship is significantly lower than that of all other compared ships. It is known that $L_W / \nabla^{1/3}$ ratio is the decisive hull form parameter at the ship speed above 25 knots, and also that ship resistance decreases with increasing L_W / B ratio (however the example of M 517 and M 536 ships revealed rather secondary influence of that parameter in the speed range in question). Also the influence of the block coefficient c_B is not large if only it is not connected with the change of the slenderness coefficient $L_W / \nabla^{1/3}$. Hence it would be necessary to investigate the relationship more precisely.

SEAKEEPING QUALITIES

Seakeeping qualities of the investigated ships were estimated by means of the model tests carried out on irregular head waves. The waves were modelled according to the two-dimensional ITTC spectrum of the significant wave height $\zeta_{W1/3} = 3{,}0\,m$ and the characteristic period $\overline{T}_1 = 6{,}8$ s. This corresponds approximately to the waves in the North Sea at the wind of 6° B. It was assumed that the ship should be capable to normal service in such conditions. The measurements were made at 6 speeds in the range of 16÷35 knots. The following characteristics were measured: heave, pitch, vertical accelerations at the bow and at the centre of gravity (C.G.), and the added resistance in waves. Values of the respective significant amplitudes $\overline{z}_{A1/3}, \overline{\theta}_{A1/3}, \overline{a}_{FA1/3}, \overline{a}_{GA1/3}$ and R_{AWS}/R_{TS} were assumed the indices of seakeeping capability of the ship as there has been no universal index of ship seaworthiness till now. Vertical acceleration is commonly considered the most important factor with respect to safety of passengers, cargo and structure. The main seakeeping characteristics of the tested ships are shown in Fig.3 and 4 [8].

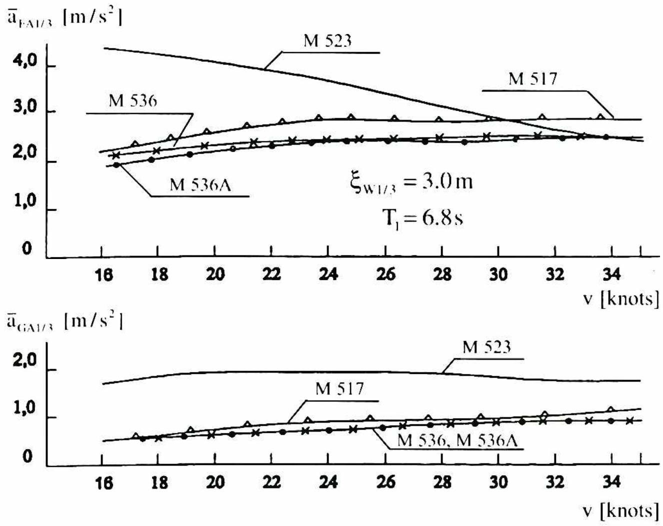

Fig.3. Vertical accelerations of the tested ships versus speed

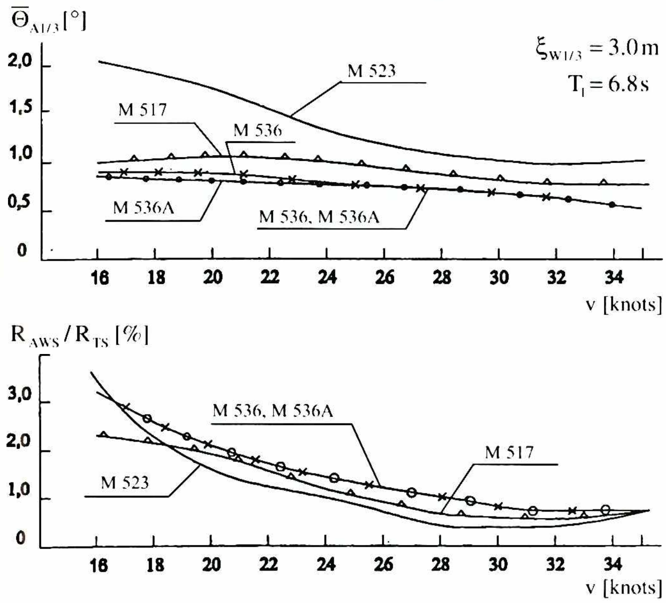

Fig.4. Pitch and relative added resistance of the tested ships versus speed

The seakeeping characteristics of the tested monohulls differ not much from each other. However, those of the catamaran are significantly worse, except of the speed range over 26 knots where pitch and acceleration values at the bow are of the same order as those of the monohulls. The relative added resistance in waves of the catamaran is smaller than that of the monohulls. As regards the monohulls, the differences between particular hull forms are relatively small – – especially in heave and acceleration values at C.G.

The M 517 hull form shows the highest amplitudes of pitch and acceleration at the bow, which are 20÷25% higher than those of M 536 hull form. Acceleration values at C.G. are very similar for all hull forms and they do not much depend on ship's speed.

The differences of the relative added resistance in waves of the tested hull forms are not large. The values of R_{AWS} / R_{TS} ratio are lower for the more slender form, M 517, than for M 536, but the difference does not exceed 10% at higher speed. To estimate the seakeeping qualities of the investigated hull forms it would be necessary to compare them with those of other ships. It is difficult as such data are very rarely published. The only available data are collected in Tab.4.

Tab.4. *Comparison of seakeeping qualities of the investigated and other ships [1, 3, 7]*

Ship	Dimension ratios		Speed	Wave parameters		Seakeeping qualities			
	L_W/B [-]	B/d [-]	V [kn]	$\bar{\xi}_{W1/3}$ [m]	$\bar{T}_1$ [s]	$\bar{Z}_{A1/3}$ [m]	$\bar{\theta}_{A1/3}$ [°]	$\bar{a}_{FA1/3}$ [g]	$\bar{a}_{GA1/3}$ [g]
Catamarans									
M 523	16	1.53	30	3.0	6.8	0.95	1.00	0.30	0.19
Seajet [7]	14.5	1.32	40	3.0	7.3	–	1.48	0.36	–
Monohulls									
M 517	9.0	3.32	30	3.0	6.8	0.54	1.03	0.25	0.10
M 536	8.0	4.14	30	3.0	6.8	0.50	0.70	0.26	0.09
Esp. [1]	7.5	6.12	35	3.2	7.6	0.38	0.80	0.41	0.14
Greek [3]	7.0	4.00	40	3.0	6.7	–	0.80	–	0.09

Notation : Seajet – *catamaran ferry of L_W – 76 m, (Finland).*
Esp – monohull ferry of L_W = 110 m, (Spanish project)
Greek – hard-chine monohull of L_W – 107,4 m (Greece)

It can be observed that the M 523 catamaran experiences similar accelerations, but smaller pitch angles, as those of the comparable catamaran „Seajet" in similar conditions. Values of the seakeeping qualities of the tested monohulls are of the same order as those of other similar ships – in spite of more slender hull forms. Absolute values of acceleration at the bow (for the catamaran : of 0.3÷0.4 g, and for the monohull of < 0.3 g) as well as at C.G. (for the catamaran : of < 0.2 g, and the monohul : of < 0.1 g) are contained within the limits admissible even for passenger ships.

PROPULSIVE CHARACTERISTICS

The catamaran was assumed to be fitted with water-jet propulsion (two units in each hull). In the case of screw-propeller propulsion only one screw could be installed in each hull because of its slenderness .This would cause too high load on the propeller and its low efficiency. The propulsive model tests of the catamarans were not conducted as their building has not been expected in Polish shipyards. The approximate calculation of water-jet propulsion for the catamaran yielded the delivered power $P_D \approx 51$ MW at 33 kn speed in trial conditions. Hence the propulsive characteristics were investigated for M 536 monohull only, but in two versions : the first one - -fitted with conventional screw-propellers, and the other - with podded propulsors of pulling type. The twin-screw driving system was provided due to small draught of the ship. In the traditional solution the screws are fixed to bare shafts with single V-struts. The respective appendage resistance amounted to 12% of the bare hull resistance at 28 kn speed and it decreased to 9.5% at 40 knots.The respective efficiencies at 33 kn speed obtained the following values :

- the hull efficiency $\eta_H \approx 0.95$
- the relative rotative efficiency $\eta_R \approx 0.97$
- the thrust deduction factor $t \approx 0.08$
- the wake fraction $w \approx 0.05$.

At the open screw efficiency ≈ 0.70 it can yield the delivered power $P_D \approx 37$ MW in trial conditions.

The investigation of the podded propulsors showed that:

- hull efficiency values for the ships with the conventional screw propellers are higher than those with the podded propulsors at the speed of below 30 knots, over this speed the values are equal; (it also results from the fact that the thrust of the podded propulsor is related to the bare hull resistance, and the thrust of the classic screw propeller – to the resistance of the hull with appendages)
- relative rotative efficiency values are practically the same.

It is difficult to estimate the propulsive efficiency η_D for podded propulsor because the detail data about the efficiency of the real propulsors in open water are not available at present. On the ground of the investigations it could be stated that the propulsive efficiency of both types of propulsors, and in consequence the delivered power is almost the same. However when choosing the type of propulsor for the ships in question, other problems should be also considered, such as ship manoeuvrability and type and location of its power plant.

CONCLUSIONS

- The presented investigations showed that the proposed hull forms for fast cargo or passenger ships for 28÷40 kn speed range are significantly better with respect to resistance than those till now designed, and not worse with regard to seakeeping qualities.
- The slenderness coefficient $L_W / \nabla^{1/3}$ is the hull form parameter decisive of the resistance of fast monohulls and it should be higher than 8. A high deadrise angle value (> 15°) and small value (< 0.5) of the block coefficient c_B is also important.
- In the above mentioned speed range the catamaran and semi-trimaran are worse than the monohull from the resistance point of view. The catamaran could be more suitable at higher speed.
- Further investigations are necessary to estimate influence of other hull form parameters on the resistance of fast monohulls.

Appraised by Tadeusz Koronowicz, Prof.,D.Sc.,N.A.

NOMENCLATURE

$\bar{a}_{FA1/3}$ - significant amplitude of vertical acceleration at fore perpendicular [a/g] [m/s²]
$\bar{a}_{GA1/3}$ - significant amplitude of vertical acceleration at C.G. [a/g] [m/s²]
B, B_W - design ship breadth [m]
B_S - distance between centre planes of catamaran's hulls [m]
C.G. - centre of gravity
c_B - block coefficient [-]
d - ship draught [m]
F_{IR} - interference factor [-]
F_n - Froude number [-]
g - acceleration of gravity [m/s²]
L, L_W - design ship length [m]
P_D - delivered power [kW, MW]
R_{AWS} - mean added resistance in waves [kN]
R_{TS} - total resistance in calm water [kN]
$\bar{T}_1$ - characteristic period of waves [s]
t - thrust deduction factor [-]
v - ship speed [knots]
w_t - wake fraction at thrust identity [-]
$\bar{z}_{A1/3}$ - significant heave amplitude [m]
Δ - ship mass [kg, t]
∇ - ship volumetric displacement [m³]
ε - relative resistance coefficient [-]
$\bar{\zeta}_{W1/3}$ - significant wave height [m]
η_D - propulsive efficiency [-]
η_H - hull efficiency [-]
η_o - propeller efficiency in open water [-]
η_R - relative rotative efficiency [-]
$\bar{\Theta}_{A1/3}$ - significant pitch amplitude [°]

$^{-}$(upper) - mean value

BIBLIOGRAPHY

1. Alaez J.A. et al.: *The seakeeping behaviour of two fast ferry ships*. RINA Int. Conf. on HSC Motions, London 1998
2. Editorial: *Entwicklung der Fährverkehre in europaischen Gewässern. Schneller Hochseetransport auf dem Wege in die Realität*. Hansa No 4, 1996
3. Grigoropoulos G.J. et al.: *Seakeeping characteristics of a systematic series of fast monohulls*. RINA Int. Conf. on HSC Motions. London 1998.
4. Heikki Sipila et al.: *Application of the slender monohull to high speed container vessels*. Proc. FAST'97. Sydney, July 1997
5. Langenberg H.: *Fast displacement ships – an economical option for high speed transportation*. Proc. FAST'95. Lübeck-Travemünde, September 1995
6. Levander K.: *Really fast freight ro-ro ships would change the market – are their economics feasible?* Source unknown.
7. Schack Ch.: *Research on semi SWATH hull form*. Proc. FAST'95. Lübeck-Travemünde, September 1995
8. Welnicki W.:*Fast containerships – an analysis of investigation results and design indications (* in Polish*)*. Ship Design &Research Centre (CTO), Techn. Rep. No. RH-2000/T-052. Gdańsk, 2000
9. Welnicki W.: *Concept and choice of design parameters of a fast containership of new generation* (in Polish) CTO Techn. Rep. No. RH-98/T-099. Gdańsk, 1998
10. Miller-Graf B.: *Schnelle Fahrgast Katamarane*. Jahrbuch STG, Vol. 83, 1989