EFFECT OF WEDGES ON THE CALM WATER RESISTANCE OF PLANING HULLS

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ABSTRACT

High speed monohulls are extensively used for short sea passenger/car transportation, near shore patrol missions, as work boats and as private yachts. The resistance characteristics of such craft can be predicted to a certain extent using the results of the few existing systematic series. In the National Technical University of Athens (NTUA), a project was initiated, a few years ago, aiming the generation of a new systematic series of planing hull forms, with improved characteristics both, in calm water and in waves. The comparative experimental evaluation of alternative hull forms led to a double-chine parent model of the NTUA series. In this paper, the effects of various stern wedge configurations on the calm water performance of the above model are experimentally investigated in a systematic way for volumetric Froude numbers up to 3.0. On the basis of the tests, the necessity of using stern wedges in planing hulls is discussed.

NOMENCLATURE

A	area of the wedge = σ B λw L
B	breadth over lower chine at transom
B_{PX}	maximum breadth over chines
D_F	drag due to the wedge
Fn	Froude number, $Fn = \frac{V}{\sqrt{gL}}$
F_∇	volumetr. Froude number, $F_\nabla = \frac{V}{\sqrt{g\nabla^{1/3}}}$
L	waterline length at rest
LCG	longitudinal center of gravity
M_F	moment due to the wedge about its trailing edge
Rm	model resistance [Kp]
t	trim at rest
Vm	model speed [m/sec]
β	deadrise angle
δ	wedge deflection angle
Δ	displacement
Δ_F	lift due to the wedge
λw	length of the wedge in percentage of the ship length
ρ	water density
σ	wedge span-beam ratio
τ	trim of planing surface
∇	displaced volume.

1. INTRODUCTION

Planing monohull vessels of ever greater size have emerged recently as a highly competitive answer to the fast sea transportation challenge. Furthermore, this kind of hull forms have been extensively used for years in near shore patrol missions, as work boats and as private yachts. For several techno-economic reasons, which are not to be discussed in this paper, high speed monohull

The model was fitted with stern wedges with lengths 2, 5, 7.5 and 10% of the waterline length. At each wedge length three different wedge span-beam ratios have been considered, σ = 1/3, 2/3 and 1. In the former cases the wedges were fixed to the side (Fig. 3). This arrangement results in improved transverse stability characteristics at the higher speeds.

In general the wedge deflection angle was 6°. Furthermore, in order to investigate the effect of the wedge deflection angle on the performance of the model, two more deflection angles 3° and 9° have been tested in the case of the full-span wedge extending 10% of the waterline length. The full testing program is presented in Table 1.

TABLE 1 : Tested wedge configurations

Condi -tion	Wedge Length λw [% L]	Wedge span-beam ratio σ	Wedge deflection angle [°]
1	-	-	-
2	2	1/3	6
3	2	2/3	6
4	2	1	6
5	5	1/3	6
6	5	2/3	6
7	5	1	6
8	7.5	1/3	6
9	7.5	2/3	6
10	7.5	1	6
11	10	1/3	6
12	10	2/3	6
13	10	1	6
14	10	1	3
15	10	1	9

4.2 The Effect of Stern Wedges

In Figs. 4 to 6 the model resistance, the running trim and the dynamic C.G. rise of the NTUA series parent model, without and with wedges, are plotted vs. model speed. Furthermore, the effective horsepower EHP requirements vs. ship speed of a 10:1 scaled vessel are given in Fig. 7.

In Figs. 8 to 11, 12 to 15 and 16 to 19, the above results for wedge lengths 5, 7.5 and 10% of L are presented, respectively.

Furthermore, in order to demonstrate the effect of the wedge deflection angle on the hydrodynamic behaviour of the hull form, the model resistance, the dynamic trim and C.G. rise and the EHP for the longest full-span wedges with deflection angles 3°, 6° and 9°, are given in Figs. 20 to 23.

Following a thorough inspection of Figs. 4 to 23 the following comments can be made:

Wedge with λw=2% of L: The shortest wedge reduces the resistance of the model at speed over 2 m/sec. The full-span wedge is more efficient resulting in a reduction of the resistance by 15% at 4 m/sec. These wedges, however, do not cause any improvement at speeds below 2 m/sec or at high speeds ($Vm \approx 5$ m/sec). The dynamic trim is also significantly affected by the addition of the short wedges, as depicted in Fig. 5. Thus, the full-span wedge and the wedge with σ=2/3 reduce the dynamic trim down to almost zero, at the highest model speed. The effect of the wedges on the C.G. rise is pronounced only at model speeds higher than 4 m/sec. EHP curves show a behavior similar to that of the model resistance curves.

Wedge with λw=5% of L: The effect of the wedges with λw=5% of L is quite similar to the shortest wedges. However, this wedge is less effective that the previous one in reducing the resistance of the model. On the contrary, the running trim by stern is drastically reduced. At high speeds the full-span wedge with λw=5% of L results in negative dynamic trims. Taking into account that, the trim of the model at rest, at the investigated loading condition, is zero, the total trim turns to be by bow.

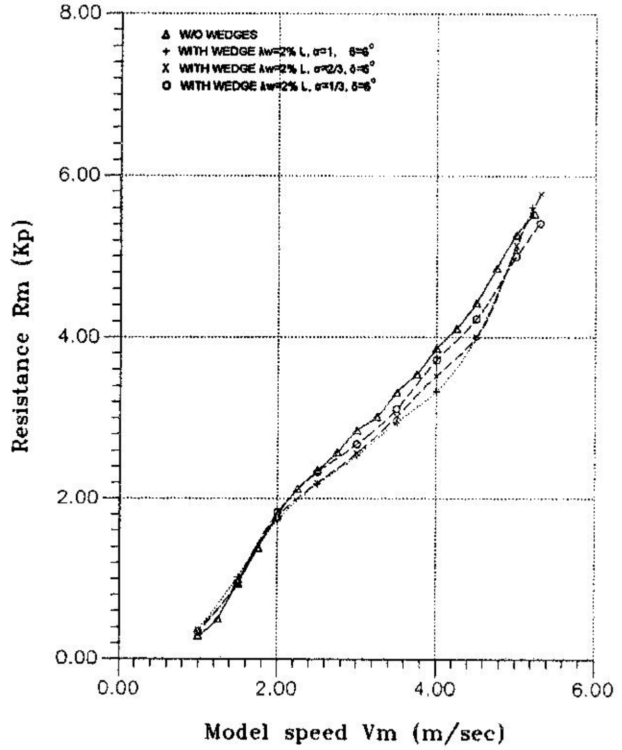

Fig. 4 Resistance of the model w/o and with wedges (λw=2%, δ=6°).

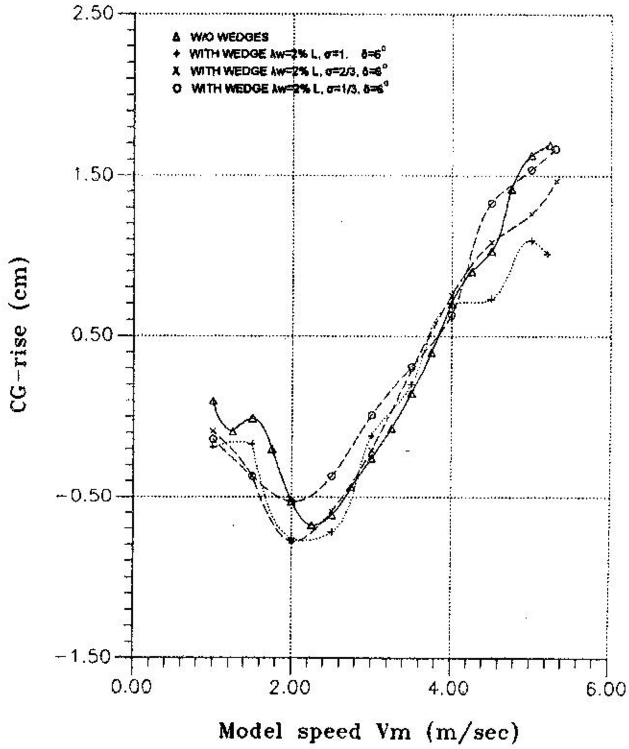

Fig. 6 C.G. rise of the model w/o and with wedges (λw=2%, δ=6°).

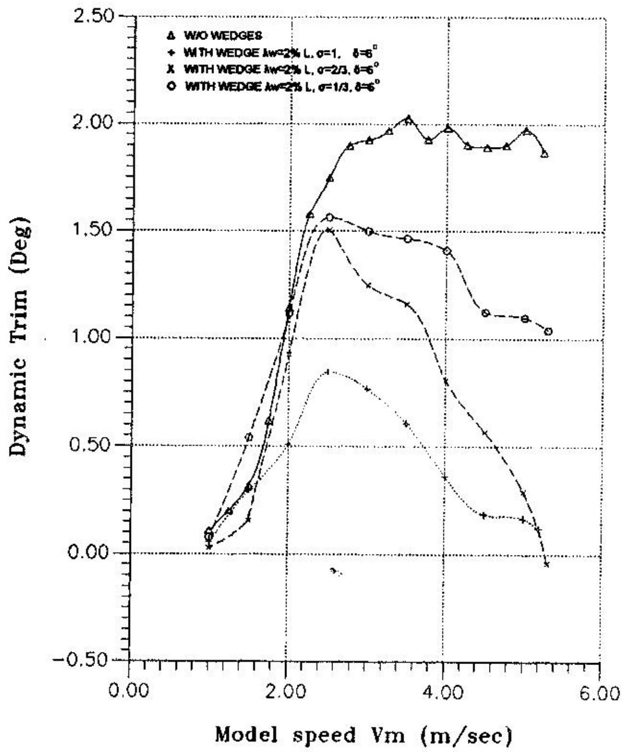

Fig. 5 Dynamic trim of the model w/o and with wedges (λw=2%, δ=6°).

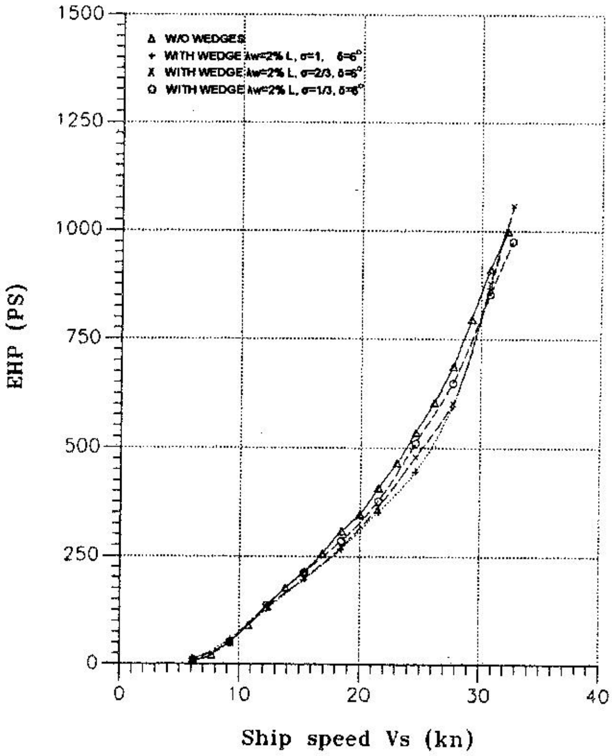

Fig. 7 EHP for a 10:1 scaled vessel w/o and with wedges (λw=2%, δ=6°).

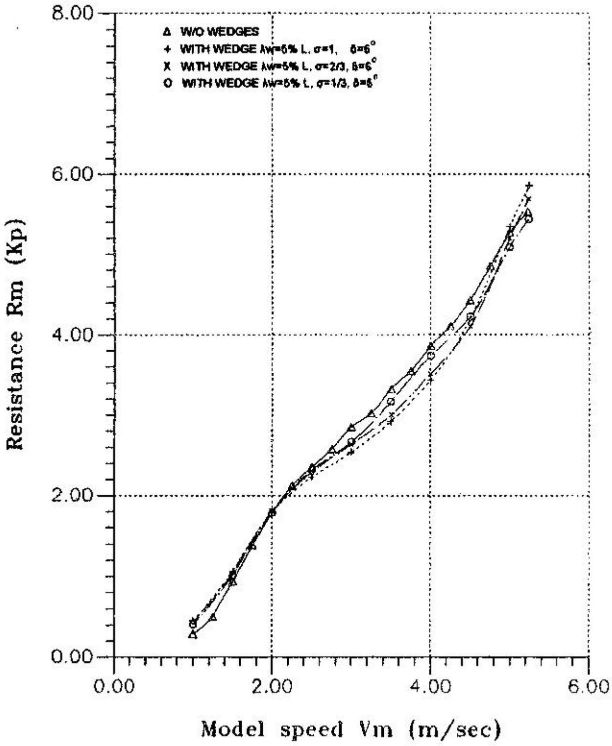

Fig. 8 Resistance of the model w/o and with wedges (λw=5%, δ=6°).

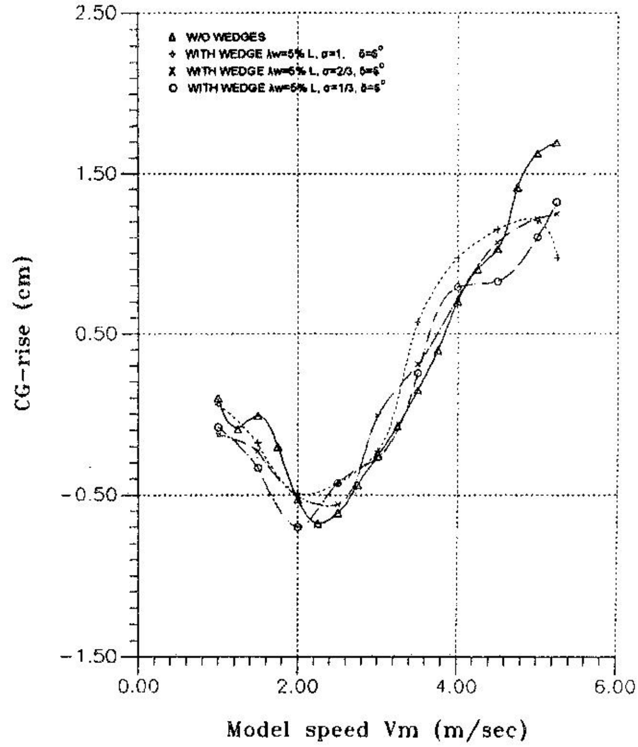

Fig. 10 C.G. rise of the model w/o and with wedges (λw=5%, δ=6°).

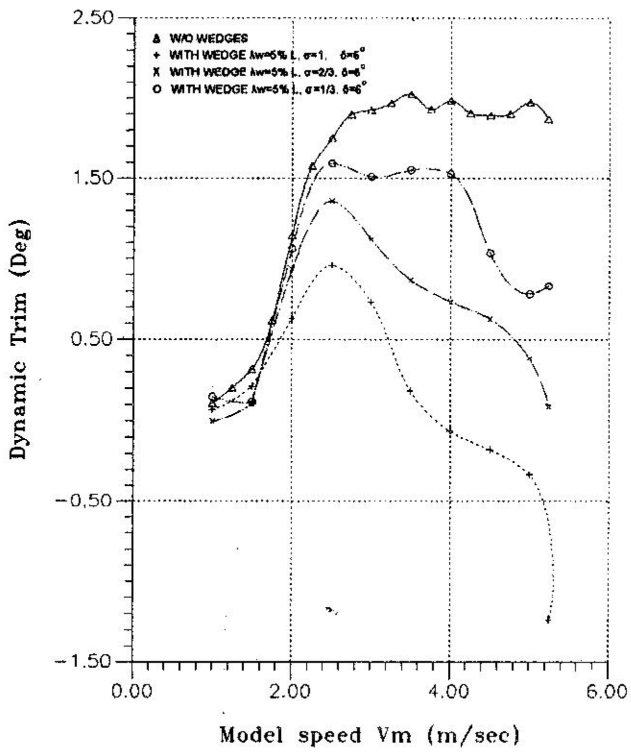

Fig. 9 Dynamic trim of the model w/o and with wedges (λw=5%, δ=6°).

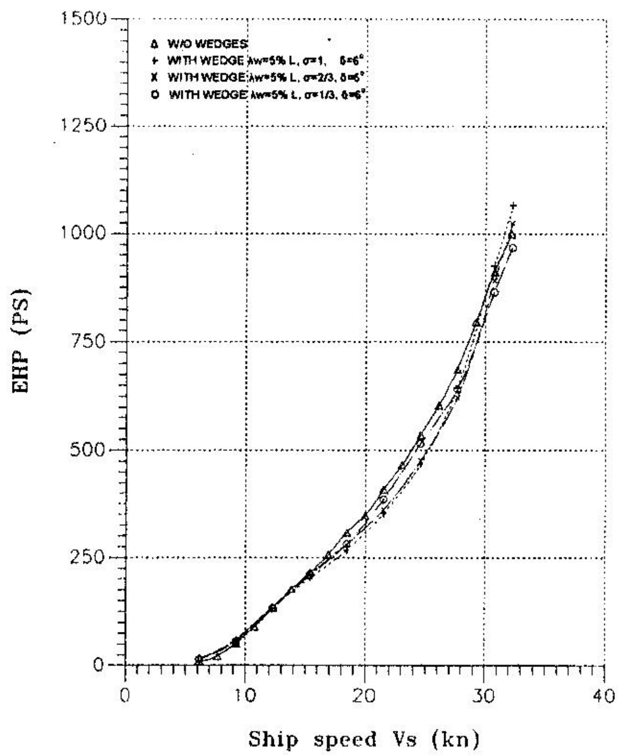

Fig. 11 EHP for a 10:1 scaled vessel w/o and with wedges (λw=5%, δ=6°).

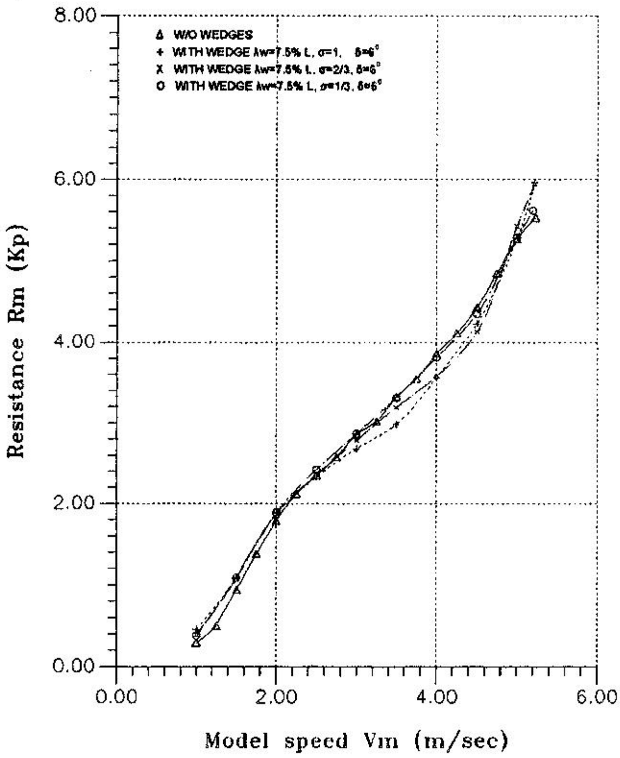

Fig. 12 Resistance of the model w/o and with wedges (λw=7.5%, δ=6°).

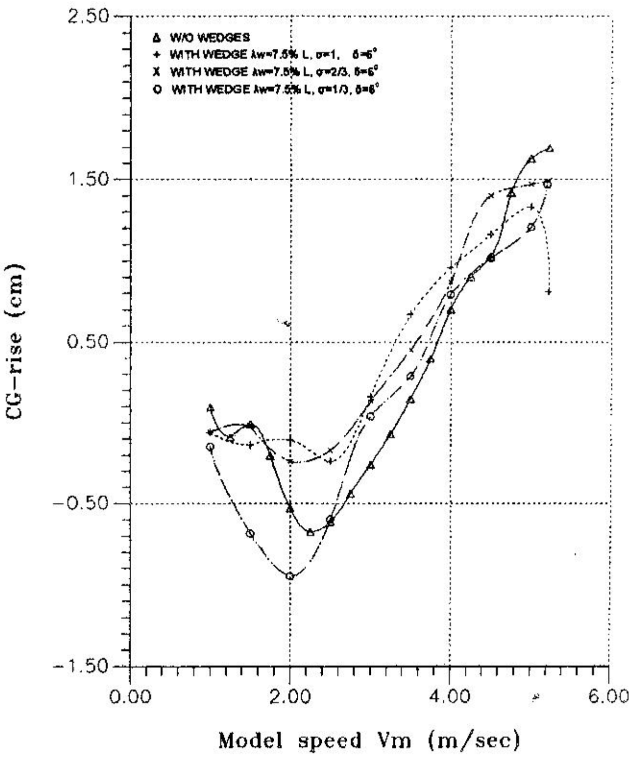

Fig. 14 C.G. rise of the model w/o and with wedges (λw=7.5%, δ=6°).

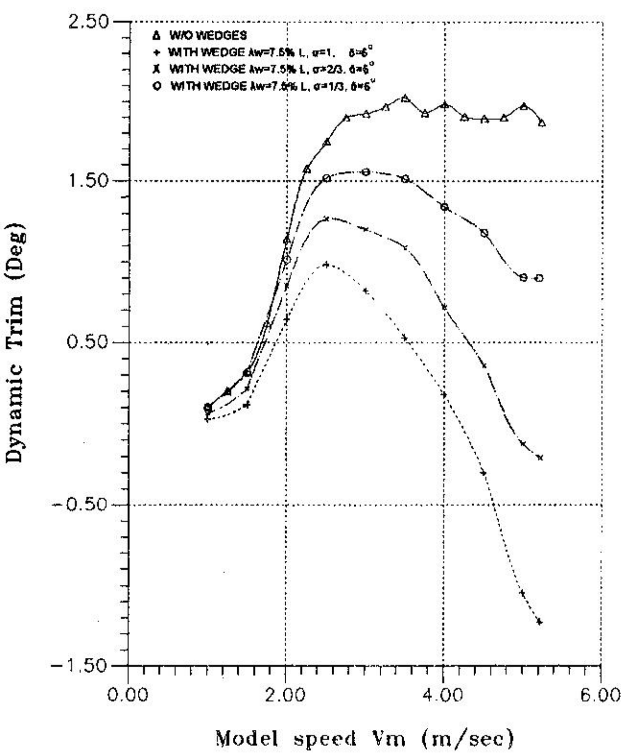

Fig. 13 Dynamic trim of the model w/o and with wedges (λw=7.5%, δ=6°).

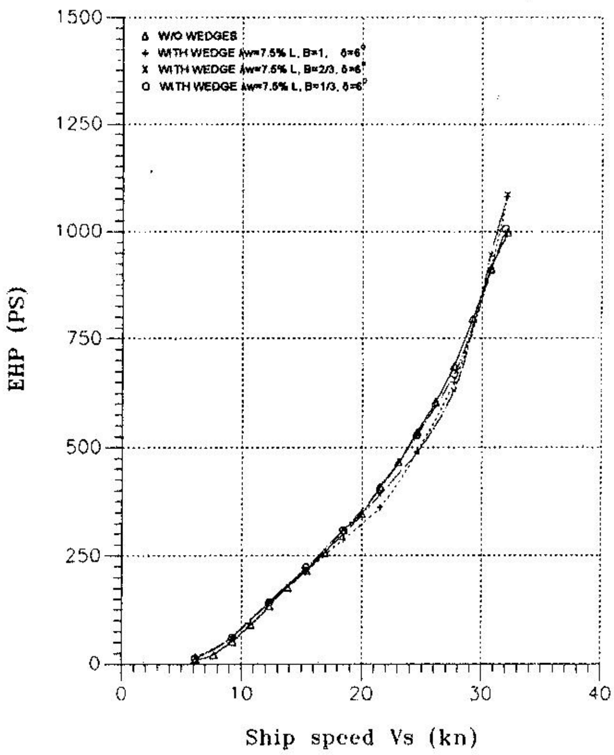

Fig. 15 EHP for a 10:1 scaled vessel w/o and with wedges (λw=7.5%, δ=6°).

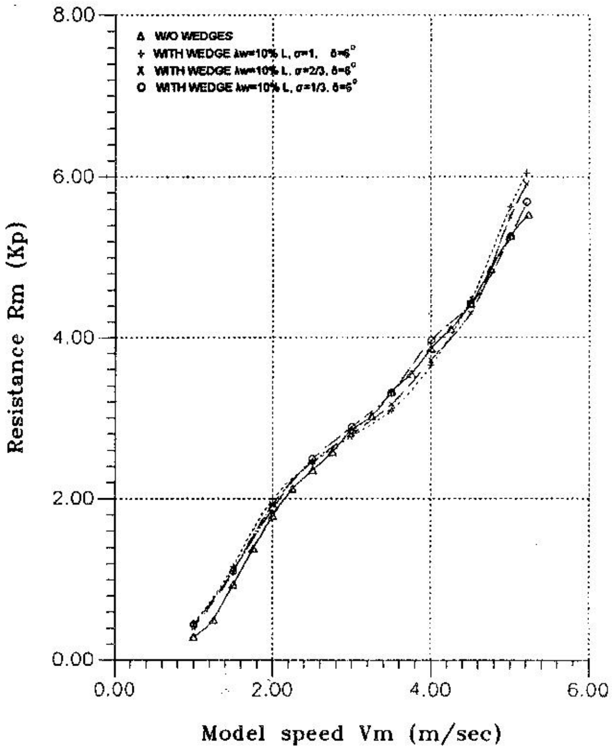

Fig. 16 Resistance of the model w/o and with wedges (λw=10%, δ=6°).

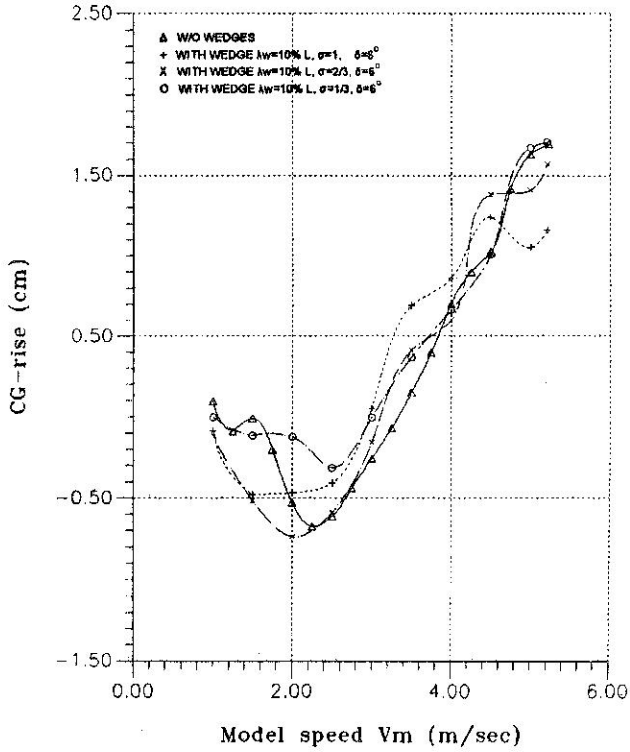

Fig. 18 C.G. rise of the model w/o and with wedges (λw=10%, δ=6°).

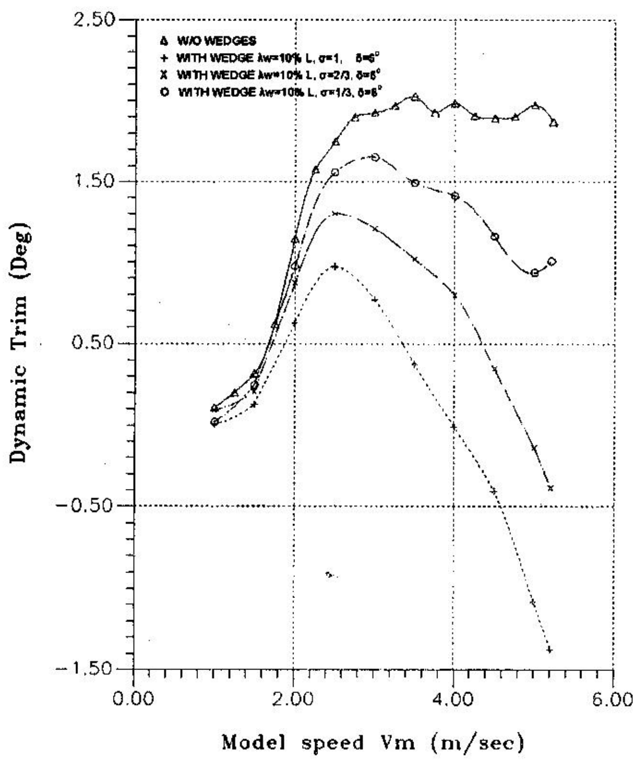

Fig. 17 Dynamic trim of the model w/o and with wedges (λw=10%, δ=6°).

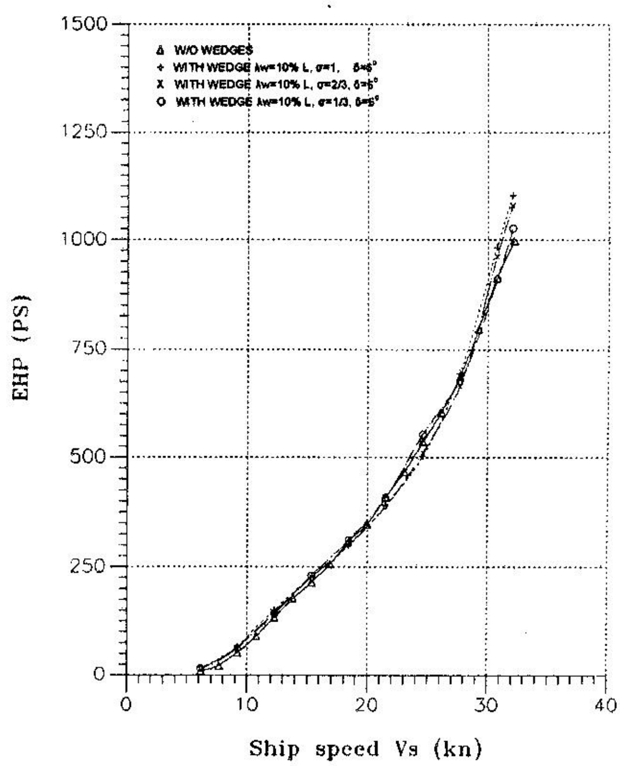

Fig. 19 EHP for a 10:1 scaled vessel w/o and with wedges (λw=10%, δ=6°).

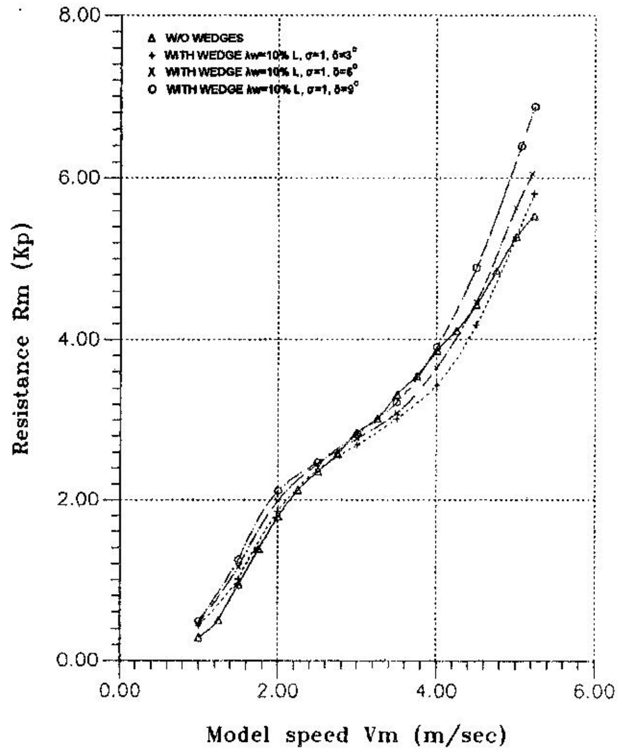

Fig. 20 Resistance of the model w/o and with wedges (λw=10%, σ=1).

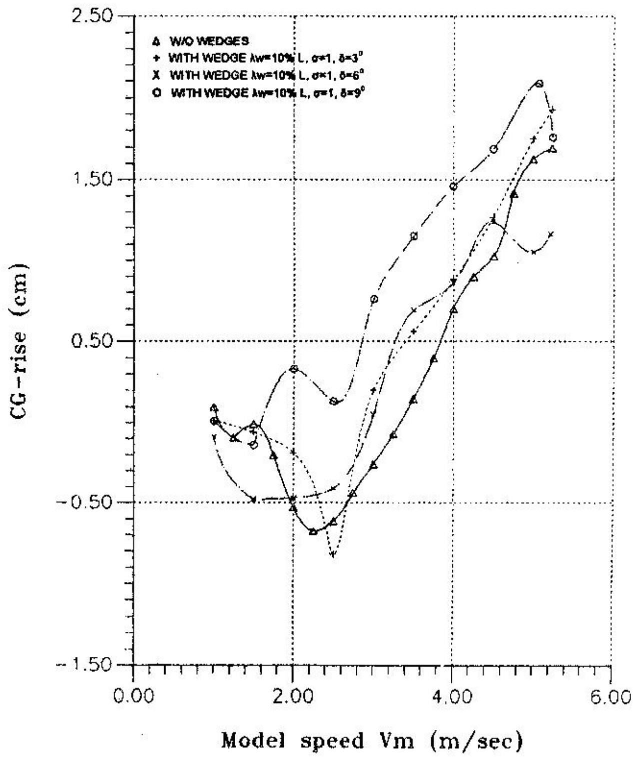

Fig. 22 C.G. rise of the model w/o and with wedges (λw=10%, σ=1).

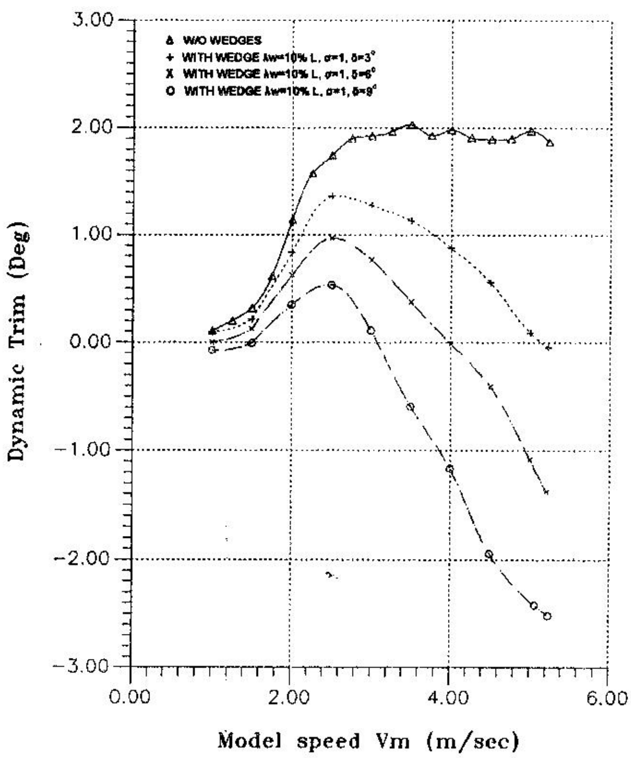

Fig. 21 Dynamic trim of the model w/o and with wedges (λw=10%, σ=1).

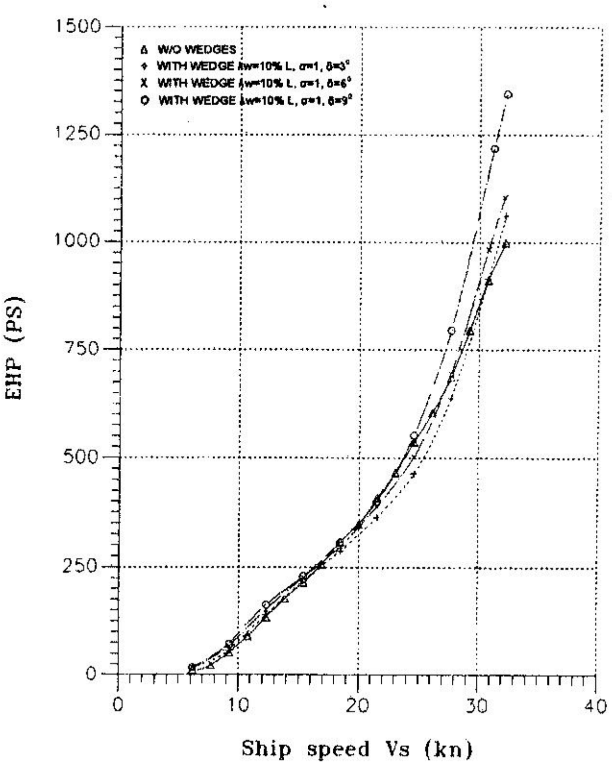

Fig. 23 EHP for a 10:1 scaled vessel w/o and with wedges (λw=10%, σ=1).

Therefore, the running trim of the model deviates from the optimum one. The resulting increase of the resistance is counterbalanced by the reduction of the resistance due to the dynamic lift produced by the wedge. The wedges of the above length reach a maximum efficiency of 10% for the full-span wedge at model speeds around 4 m/sec. These wedges do not have any considerable influence on the dynamic C.G. rise.

Wedge with λw=7.5% of L: The general trends noticed in the previous cases of wedge lengths are also observed in the case of the wedges with λw=7.5% of L. The maximum efficiency of the wedge is restricted to a 5% reduction of the model resistance, which, however, occurs at the same model speed. At the highest speed tested the model resistance is somewhat increased especially for the full-span wedge. Both, the running trim and the C.G. rise are seriously affected by the presence of these wedges.

Wedge with λw=10% of L: The longest wedges do not affect significantly the calm water resistance of the model. On the contrary, the running trim by stern is drastically reduced, and at the same time the C.G. is raised.

Wedge with varying deflection angles: The effect of the wedge deflection angle has been examined only for the longest wedges. According to the results presented in Figs. 20 to 23, the smallest deflection angle is recommended. This deflection angle results in a 10% reduction of the resistance at speeds near 4 m/sec.

Furthermore, a thorough comparative inspection of Figs. 8 (σ=1, λw=5% L, $\delta=6^o$), 12 (σ=2/3, λw=7.5% L, $\delta=6^o$) and 20 (σ=1, λw=10% L, $\delta=3^o$) leads to the conclusion that both full-span wedges exhibit a very similar behavior. Their efficiency is superior over that of the partial-span wedge with σ = 2/3.

5. DISCUSSION AND CONCLUSIONS

As it has been demonstrated by Savitsky [15], the performance of prismatic planing hulls in calm water is dominated by the displacement and its longitudinal distribution expressed by LCG, the breadth over chine and the deadrise angle. In the case of non-prismatic hulls with varying deadrise, the respective longitudinal distribution of breadths over chines and deadrise angles should be taken into account. For any given combination of these design parameters the hull is planing at any speed with a specific dynamic trim. Thus, the problem of optimizing the design of a planing hull form is reduced to finding out the optimum combination of these parameters, resulting in reduced horsepower requirements. The achieved dynamic trimming angles in that case, are closely associated with the specific hull form, so that it could be said that, instead of seeking for reduced resistance, the designer aims at the determination of the associated dynamic trim over speed curve.

Since the displacement and the LCG are usually pre-set by the user's requirements, the main task of the designer is to determine an optimized combination of longitudinal distributions of breadths and deadrise angles, resulting in reduced calm water resistance. When this objective can not be achieved, stern wedges or adjustable trimming tabs should be used to reduce the running trim by stern of a planing hull. The stern wedges are simple constructions and they can produce high lift forces, resulting in an improved hydrodynamic performance of the vessel in a limited speed range. On the contrary, the trimming tabs permit the fine tuning of the dynamic trim to its optimum value, corresponding to the minimum resistance for a given speed. However, their constructional details do not allow for very heavy loading.

In the case of the parent hull of the NTUA series, it seems that for the tested loading condition, the model without the wedges runs at a nearly optimum trim. Thus, the effect of the wedges on the resistance is relatively small and can be either positive or negative.

Furthermore, the use of simple formulae for the determination of the geometrical characteristics of the stern wedges is recommended only as a preliminary working tool. Tank tests are the only means in deciding upon the necessity and the appropriate size of the stern wedges.

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designs of both, commercial car-ferries and naval vessels are presented with lengths around 100 m, displacements in excess of 1000 mt and speeds in the 40 knot range.

Thus, the creation of a new systematic series of planing hulls with improved resistance and seakeeping characteristics, a project which was initiated some years ago at the Laboratory for Ship and Marine Hydrodynamics of the NTUA, has gained increased interest.

On the way to the creation of the new systematic series, a series of alternative hull forms, with rounded bottom, single chine or double chine and narrow or wide transoms were experimentally evaluated in a systematic way for volumetric Froude numbers F_V up to 3.0 [1]. According to the results of the above investigation, the double-chine, wide-transom hull form proposed by Savitsky, Roper and Benen [2] was clearly promoted to become the parent model of the new series.

Following the design of the parent model and before proceeding to the design, construction and testing of all the members of the NTUA series, the effect of hull appendages (spray rails, stern wedges) on the calm water characteristics of the parent hull, was experimentally investigated. The performance of the model without and with spray rails has been presented and discussed by Grigoropoulos and Loukakis [3]. In the present paper the effect of various stern wedge configurations on the calm water performance of the above model is experimentally investigated, in a systematic way for volumetric Froude numbers up to 3.0. On the basis of the tests, the necessity of using stern wedges in planing hulls is discussed.

2. STATE-OF-THE-ART REVIEW

The use of stern wedges and adjustable trim tabs as means for controlling the trim of planing craft and optimizing their performance, is widespread. Brown [4] presented some simple expressions for the increase in lift, drag and moment due to flaps in general. According to that study, the flap lift is given by

$$\Delta_F = 0.046\,\delta\,A\left[\rho/2\right]V^2 \qquad (1)$$

In addition, the pressure on the wedge causes a drag which is proportional to the wedge lift

$$D_F = 0.0052\,\Delta_F\,(\tau+\delta) \qquad (2)$$

The hydrodynamic wedge moment measured about the trailing edge of the wedge is given by

$$M_F = \Delta_F\left[0.6\,B + L\,\lambda w\,(1-\sigma)\right] \qquad (3)$$

According to (1) the product δ A controls the wedge lift. In addition, from equation (2), it turns out to be more efficient to generate wedge lift by means of wedge area rather than flap deflection, as it is also concluded in [4]. However, the main difficulty faced is the definition of the appropriate "effective" deadrise angle and the respective "effective" breadth for non-prismatic hull forms with warp, to be used for the estimation of the running trim of the vessel [4-6].

A relation similar to (1), where the coefficient 0.046 has been reduced to 0.044, has been proposed by Hubble [7].

The influence of wedges on the performance characteristics of two narrow transom planing hulls of the DTMB Series 62 [8] with L/B_{PX}=3.06 and 4.09 has been experimentally investigated by Cole and Millward [9,10]. The authors carried out tests using full beam wedges with lengths λw=5, 10 and 15% of L and deflection angles δ=2°, 5° and 10°, for a range of displacements and LCG positions, at speeds with F_V=1.0÷4.0. The optimum wedge length was found to fall in the range of 5% to 10% of L, tending to lower values for lighter displacements and forward shifted LCG positions. The optimum wedge angle reaches a maximum of approximately 10° at the heavy displacement. A maximum reduction of 25% in the resistance of the model with the lower L/B_{PX} has been achieved.

Wang [11] assumed that the wedge is another independent planing surface running at a trim angle of δ (instead of τ). He, then, applied Savitsky's theory [5] on Brown's data and arrived at the following relations for the estimation of the lift, the drag and the moment produced by full-span wedges:

$$\Delta_F = \left(C_{LOF} - 0.0065\,\beta\,C_{LOF}^{0.6}\right)B^2\left[\rho/2\right]V^2 \qquad (4)$$

$$D_F = A\ \tan\delta\ f(\delta)\left[\rho/2\right]V^2 \qquad (5)$$

$$M_F = \Delta_F\left[0.3\,B + \lambda w\,L\right] \qquad (6)$$

where

$$f(\delta) = 2\,\delta/90 \qquad \text{for } \delta < 5^\circ$$
$$= 0.111 + 0.0169\,(\delta - 5) \qquad \text{for } 5^\circ \le \delta \le 15^\circ$$

$$C_{LOF} = \delta^{1.1}\left[0.012\,c^{1/2} + 0.0055\frac{c^{2.5}}{F_B^2}\right]$$

$$c = 0.3 + \lambda w\,L/B, \qquad F_B = V/\sqrt{gB}$$

Chen et al. [12] presented results of systematic tests with wedges at the stern of flat plate planing surfaces. They concluded that Brown's formulae [5] for the estimation of wedge lift Δ_F and drag D_F are suitable only for wedge length-beam ratio 0.2, while Wang's formulae are better for higher length-beam ratios.

Wellicome and Jahangeer [13] proposed a linear numerical method for estimating the pressure distribution over the wetted surface of a planing hull, based on the representation of this area by an assemblage of rectangular elements of constant pressure. Their method is flexible and allows for the numerical investigation of the effect of hull details (wedges, steps) on calm water performance. The authors presented some results referring to a wedge fitted on a two-dimensional flat plate.

3. DESCRIPTION OF THE HULL FORM

The length-beam ratio (L/B) is the dominant parameter in the generation of a systematic series of planing hull forms, when both their resistance and seakeeping characteristics are to be examined. On the basis of the various existing systematic series and of many existing hull forms, it was decided the L/B ratio to range between 4.0 and 7.0. The L/B ratio of 5.5 was used for the parent hull form of the series. In order to select the parent hull form of the new series, single chine, double chine and rounded bilge transverse sections, combined with mostly constant or varying deadrise angles, were used.

The finally selected parent hull has two successive chines running forward of the transom up to 70% of the hull length, while molded, highly flared lines form the bow region. It has a wide transom and a varying deadrise angle distribution, from 10° to about 70° stern to bow, as suggested by Savitsky, Roper and Benen [2].

The combination of hard chines in the stern with molded lines in the bow, for ships sailing at speeds with F_∇ in the 2.5 to 3.0 range, have also been proposed by Yegorov et al. [14]. The lines plan of this model is depicted in Fig. 1.

A wooden model of the parent hull forms, with an overall length of about 2.2 m, has been constructed and tested for speeds up to 5 m/s model scale (respectively, $F_\nabla \le 3.0$).

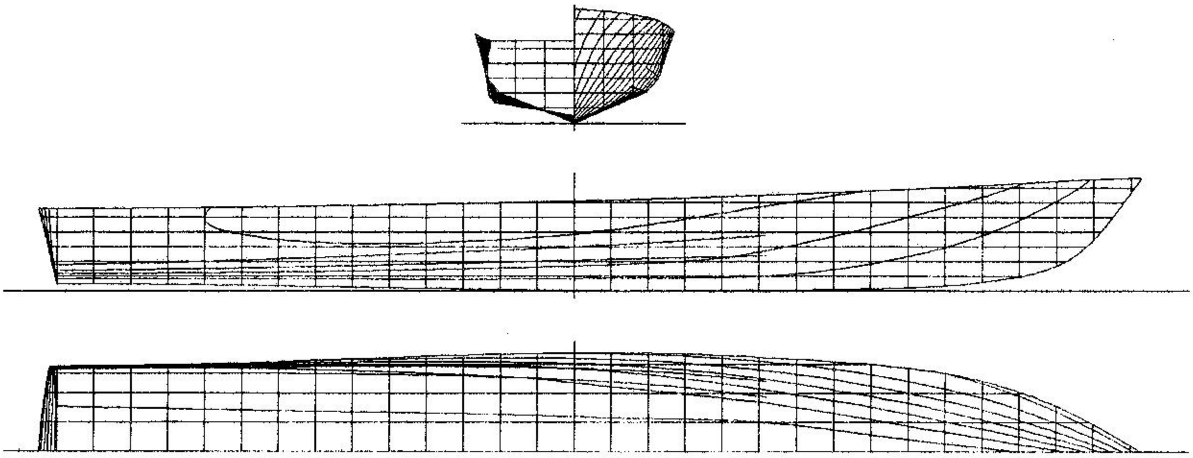

Fig. 1 : The lines plan of the parent hull of the NTUA systematic series.

4. TEST PROGRAM

4.1 Testing Condition

The systematic investigation of the calm water characteristics of the parent hull form is carried out at five loading conditions C1 to C5, as shown in Fig. 2.

	C4 Δ = 29.72 Kp LCG=-0.35 m t ≈ 0.6° by bow	
C1 Δ = 21.51 Kp LCG=-0.29 m t ≈ level keel	C3 Δ = 29.72 Kp LCG=-0.29 m t ≈ level keel	C2 Δ = 36.19 Kp LCG=-0.29 m t ≈ level keel
	C5 Δ = 29.72 Kp LCG=-0.20 m t ≈ 0.9° by stern	

Fig. 2 : Testing conditions for the parent model

For the present study the central condition C3 has been selected. In all cases of the present study the model was equipped with spray rails as described in [3].

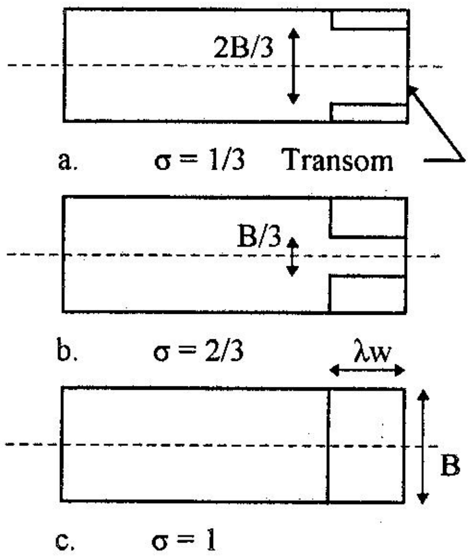

Fig. 3 : Wedge configurations tested.