INTRUDER: A DEVICE TO IMPROVE HULL PERFORMANCES

A Mancini, **A Moriconi**, Insean - Italian Ship Model Basin, Italy

SUMMARY

The intruder is a device that has been used for a long time now on big fast monohulls like "Acquastrada". It consists of a small vertical thin plate positioned under the transom of a planing or semi-planing hull, jutting out just a few millimetres. It is able to improve hull performances assuring a smaller drag thus a higher speed for the same installed power. For this reason, for its working and installation simplicity, as well as for its low cost, the intruder is becoming increasing popular even with small working and sports crafts.
In order to improve the knowledge about the hydrodynamic effects caused by this device, some tests have been performed at INSEAN using three planing and semi-planing models.
As the results of tests show, the intruder changes significantly the dynamic trim of the hull and it raises the stern. These effects can reduce the wave pattern and thus the drag. The improvements are larger in the pre-planing phase ($1<F_{n\nabla}<2.5$) where drag reductions - of more than 20% - have been measured.

NOMENCLATURE

A_P	Planing bottom area (m^2)
AR	Aspect ratio
B_{PT}	Transom breadth
B_{PX}	Maximum breadth over chines (m)
C_F	Frictional resistance coefficient
C_R	Residuary resistance coefficient
C_T	Total resistance coefficient
$F_{n\nabla}$	Volumetric Froude Number
g	Acceleration of gravity (9.803 m/s^2)
L_{PR}	Projected chine Length (m)
L_{WL}	Length of Waterline (m)
P_E	Effective power (kw)
R_n	Reynolds Number
R_T	Total Resistance (N)
S	Area of wetted surface (m^2)
S_i	Protrusion of intruder (m)
V	Speed of the model (m/s)
β	Deadrise angle of planing bottom (degree)
β_T	Deadrise angle at transom (degree)
λ	Scale ratio
∇	Displacement Volume (m^3)
ν	Kinematic viscosity (N s m^{-2})
Δ	Displacement (N)
ϑ	Static trim angle (degree)
τ	Dynamic trim angle (degree)

1. INTRODUCTION

A small vertical thin plate positioned under the transom jutting out the bottom a few millimeters, is what is very often called intruder in naval world today. The hydrodynamic effect it causes enables to use it instead of the more ordinary flaps. Like these they can stabilize the hull and correct the trim, but with the advantage that the performances are often better.
Up till now in literature there is still scarce information about a quantitative evaluation of its advantages. In order to add something more to what today known about the hydrodynamic effects caused by this device, some comparative tests with and without intruder have been performed at the Italian Ship Model Basin using three planing and semi-planing models.

2. ORIGIN AND HISTORY OF INTRUDER

The intruder does not have a unique definition yet: sometimes is also named interceptor or something else. It comes from a device used in aeronautics called “Gurney Flap”, from a racing car pilot name, Dan Gurney, that, at the end of the sixties, installed it on his cars to increase ailerons lift. Beginning from the half of the seventies it was studied and developed in aeronautics research [1], and the first applications were on the wings of DC10. It was a vertical plate positioned on the trailing edge of the wing, jutting out a small quantity, generally included from 1 and 2% of the wing chord.

Experimental studies [2] [3] [4] have proved that the Gurney Flap positioned on traditional profiles can determine, for a specific angle of attach, an increase of the pressure on the face and, above all, an important decrease on the top surface, that is a high increase of the lift, that for some profiles can exceed 50% [5]. Besides, if the protrusion of the plate is less than 2% of the chord, the increase of resistance is negligible, because the device is completely dipped in the boundary layer. For the same lift coefficient produced, the increase of Gurnery Flap protrusion delays separation, causing a further increase of the profile efficiency.
These effects are caused by an alteration of Kutta-Joukowsky condition (flow uniformity downstream a profile): the Gurney Flap produces a little upstream

separation region, and two downstream controrotating vortices, and then the chord profile is longer near the trailing edge.
This vorticity, added to the profile peculiar one, brings about a higher velocity gradient between the face and the top surface of the profile, and produces an increase of pressure gradient and then of lift [6].

Gurney Flap can be used even as stabilizer: a couple of theme, appropriately positioned, has been put on many helicopter types. [7].
This device has been used in naval field since many years on "deep V" high speed monohull, such as the "Acquastrada" ferryboat, as trim corrector, stabilizer and backing device for steering the ship, and it has been named "interceptor". Today, even if with some changes, it is often used on planing and semi-planing high speed little vessels, in order to improve their performances, and is often named "intruder".

3. TESTED MODELS.

At the Italian Ship Model Basin (INSEAN), intruder has been tested on three models: two standard planing ones and one catamaran, that we call for simplicity model A, B and C, with scale λ 5.5, 10 and 8 respectively.
The L_{PR}/B_{PX} ratios (Projected chine Length / Maximum breadth over chines) of the first two tested models, are typical of a 10-15 meters long yacht and a 20 meters big one respectively. We have to underline that these ratios are relative to the planing surface determined by the chine, how is usual for planing hulls. Model C, very different from the others, is a particular case, but it has shown similar results.

	A	B	C*
L_{PR}/B_{PX}	2.88	4.72	12.09
$A_P/\nabla^{2/3}$	6.15	3.54	-----
β	16°	14.8°	14.5°
β_T	12.7°	7.9°	14.5°
$L_{WL}/\nabla^{1/3}$	4.28	5.65	5.87

* : Parameters related to only one hull
(L_{WL} related to no intruder tests)

Table 1: A, B, C. models dimensionless parameters.

In table 1 typical dimensionless parameters are reported for the three models,
During the tests resistance and heaves have been measured for different speeds in accordance with Insean standard procedures [8]. The obtained results, in order to make the comparison easier, have been appropriately made dimensionless. By speed the Volumetric Froude Number has been calculated:

$$F_{n\nabla} = \frac{V}{\sqrt{g\nabla^{1/3}}}$$

where V is speed, g gravity acceleration and ∇ is the displacement volume. The resistance has been simply devided by displacement, obtaining the resistance coefficient R_T/Δ.

4. FIXED INTRUDER.

4.1 EXPERIMENTAL DATA

Model A has been tested from 2.15 to 3.45 Volumtric Froude Number, without intruder at ϑ=0°, whereas with it both at $\vartheta=0°$ and at $\vartheta=1.15°$ (trim by the stern), using the ratio $S_i/L_{PR}=1.03\times10^{-3}$, where S_i is the intruder protrusion.
In figure 1 R_T/Δ and dynamic trim angle τ curves versus the Volumetric Froude Number are represented.

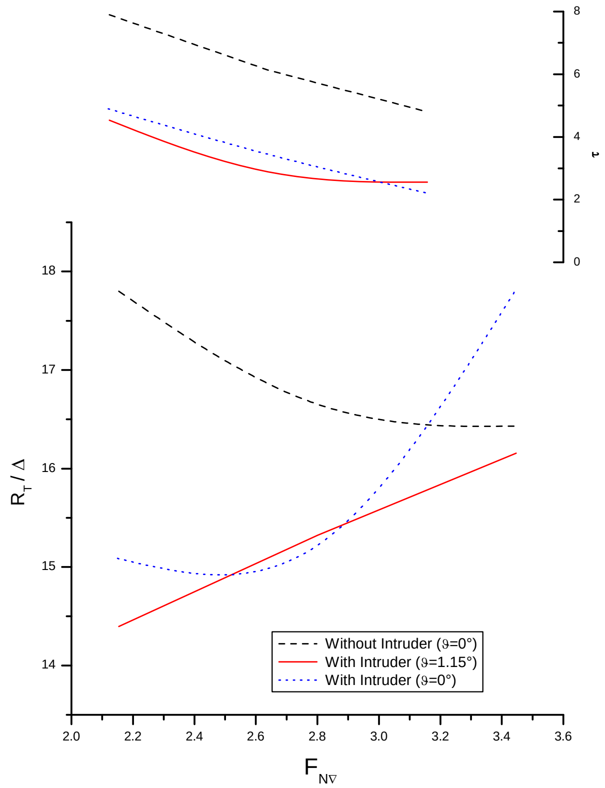

Figure 1: Mod A – Experimental data, with and without intruder.

Comparing the two broken lines ($\vartheta=0°$), intruder advantage is very clear at lower Volumetric Froude numbers, but it decreases when speed increases, as far as $F_{n\nabla}=3.1$, where there is a reversal of trend. In the same figure the continues line represents the coefficient resistance curve obtained at $\vartheta=1.15°$: the starting positive trim (by the stern) causes a higher improvement at very low speeds, about 19% at $F_{n\nabla}=2.2$, advantage that decreases if speed increases remaining obvious for all tested field anyway.
Tests on model B have been carried out from $F_{n\nabla}=1.73$ to $F_{n\nabla}=2.67$. Without device it has been tested at ϑ=-0.5° (trim corresponding to the smallest resistance at $F_{n\nabla}=1.9$), while with intruder ($S_i/L_{PR}=0.76\times10^{-3}$) at $\vartheta=0°$.

Curves trend in figure 2 is slightly different from the preceding case: the improvement starts from 9.5% at $F_{n\nabla}=1.7$, increases and grows steady, about 17%, for the remaining tested $F_{n\nabla}$ (from 2.0 to 2.7).

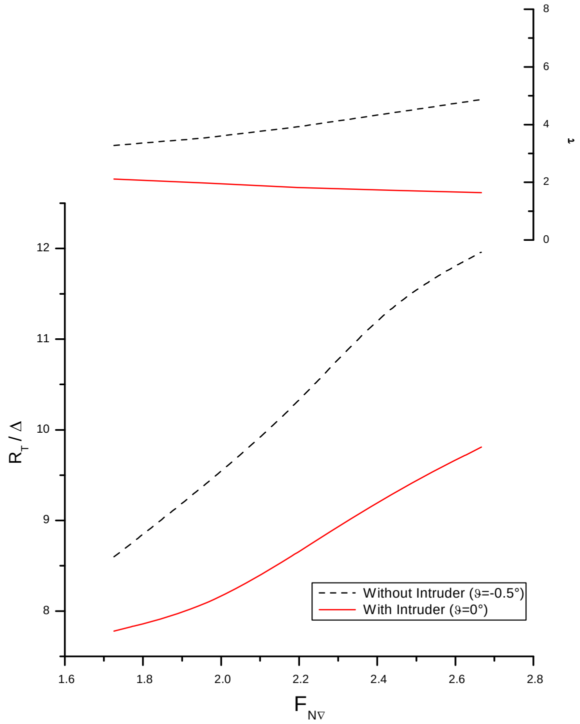

Figure 2: Mod B - Experimental data, with and without intruder.

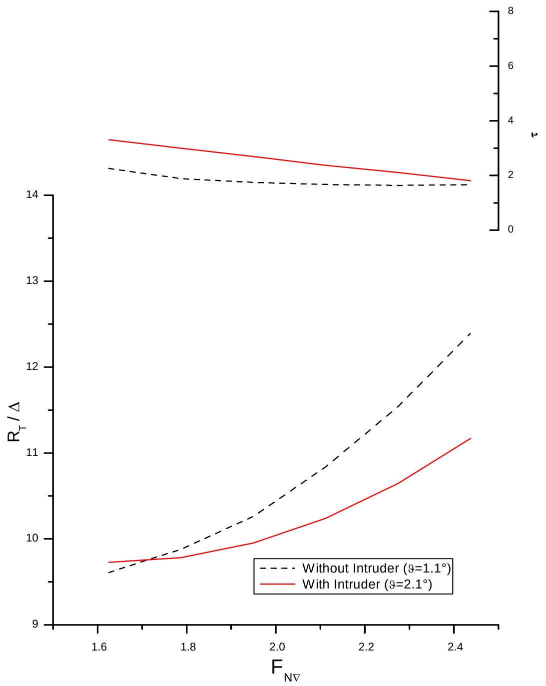

Figure 3: Mod C - Experimental data, with and without intruder.

As regards the catamaran (model C) the two different tested trims, with and without intruder, are respectively $\vartheta=1.14°$ and $\vartheta=2.12°$, with $S_i/L_{PR}=1.14\times10^{-3}$, from $F_{n\nabla}=1.63$ to $F_{n\nabla}=2.44$. Curves shown in figure 3 highlight that, at very low Volumetric Froude Numbers, intruder causes a slight worsening, trend that soon after changes when speed increases, getting on for 10% at $F_{n\nabla}=2.4$.

In described figures, dynamic trim angle curves furthermore are shown, always versus Volumetric Froude Number: in all tests with intruder τ is less.

4.2 DATA ANALYSIS .

Analysing the obtained experimental results, it is necessary to notice that the Volumetric Froude Number fields are very different, because they correspond to the real functioning speeds of full scale ships. For example model A - short and wide - has been tested up to $F_{n\nabla}=3.4$, (the starting planing $F_{n\nabla}$ is about 2.5), experiments with model B - longer and more narrow – have been done up to $F_{n\nabla}=2.6$, while the catamaran has been tested up to $F_{n\nabla}=2.44$. These differences do not prevent us from doing any comparisons and from drawing common conclusions, such as the clear advantage caused from intruder use, even if it is in percent very different in the three cases if Volumetric Froude Number varies.

There are no studies in depth that justify the positive effect of intruder from a quantitative point of view. But we may suppose the qualitative principle of operation: on the analogy of Gurney Flap [9] in aerodynamic field, we may think that a small separation region forms upstream intruder. It is a kind of dynamic wedge that modify significantly the pressure field just below the bottom of the hull, producing a higher hydrodynamic support.

This hypothesis is supported for example by figure 4, that shows model C at $F_{n\nabla}=2.44$ without and with intruder: a small plate jutting about one thousandth of the hull length raises the stern about 5% of length itself.

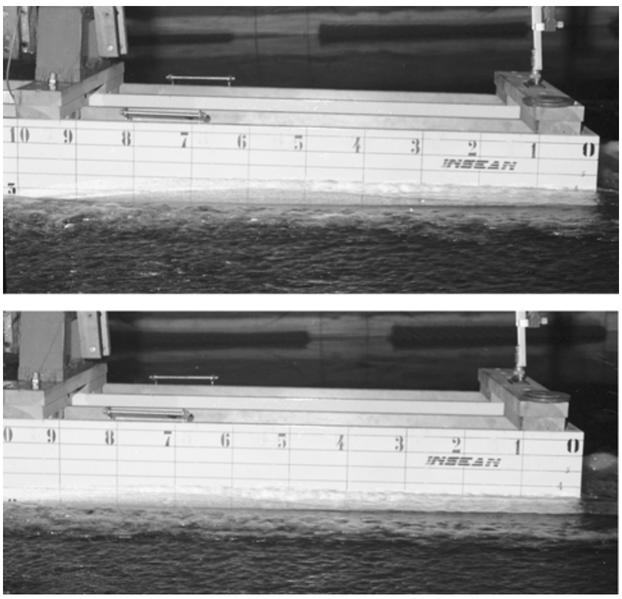

Figure 4: Model C: Profile of stern wave at $F_{n\nabla}=2.44$ without (upper photograph) and with intruder (lower one).

The overall effect is comparable to that produced by big flaps, but the added resistance is very lower. Intruder in fact – even if it is perpendicular to the flow – works completely deep in the boundary layer. Tests have shown that both wet length and surface are usually higher (even more than 20%); but the variation of length changes the friction resistance coefficient C_F very little in percent, whereas the increase of surface conditions greatly the total resistance coefficient C_T, that decreases considerably, where C_F calculated in accordance with ITTC '57 [10] is:

$$C_F = \frac{0.075}{(Log_{10} R_n - 2)^2}.$$

Mentioning

$$C_T = C_F + C_R = \frac{R_T}{\frac{1}{2}\rho S V^2}$$

it is evident that the advantage caused by intruder is due to a decrease of the residuary resistance coefficient (C_R), that, besides, is very important for a high speed hull, producing even more than 50% of total resistance.
This kind of analysis is confirmed by experimental observations; in figure 5, for instance, is clear that using intruder the waves are lower, that generally means lower C_R.

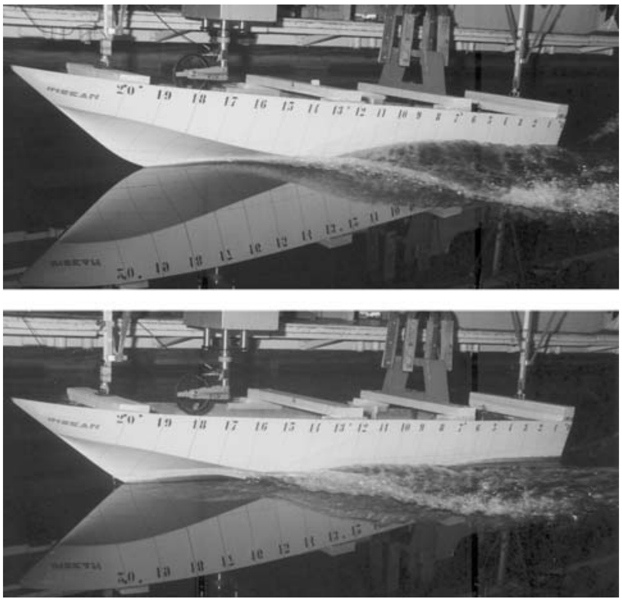

Figure 5: Model B at $F_{n\nabla}=2.20$ with intruder (upper photograph $S_i/L_{PR}=0$, $\vartheta=-0.5°$) and without (lower one $S_i/L_{PR}=0.76\times10^{-3}$, $\vartheta=0°$).

By the obtained graphs is clear that positive effect of intruder is more evident in pre-planing range ($1<F_{n\nabla}<2.5$). Looking at curves, three models have differences in behaviour, mainly because they have quite unlike geometry and so they plane at different Volumetric Froude Numbers. Model A for example at $F_{n\nabla}=2.2$ is in pre-planing range, therefore intruder produces a 20% gain nearly, soon after full planing starts, and the advantage decreases quickly. Model B instead, longer and more narrow, has a larger pre-planing range, indeed the advantage caused by intruder extends over $F_{n\nabla}=2.2$. If model B tests had been performed also at higher Volumetri Froude Numbers the two curves had got near and after intersected, but tests speeds had been choosen in accordance to the real speed of corresponding full scale ships.

5. MOBILE INTRUDER: COMPARISON WITH FLAPS.

5.1 EXPERIMENTAL DATA

As already said, intruder use can greatly improve a hull performances, but it is very often difficult to foresee its efficacy, and above all it can considerably depend on its protrusion, especially for hulls that works in a large speed range. It is sometimes suitable to use a variable protrusion of the device, as a function of speed, on the analogy of flaps, whose pressure plane is movable.
In order to evaluate the efficacy of intruder protrusion variation and to compare it with a couple of flaps, some tests have been performed on model A. It has been chosen because of its very large speed range. Tests have been done at $F_{n\nabla}=2.15$, 2.80 and 3.45, at $\vartheta=0°$, varying both intruder protrusion and flaps angle. As regards tests with intruder they have been performed also at $\vartheta=1.15°$. Used flaps were commercial ones with $AR=2$ (width=27% of B_{PT}, chord=2.3% of L_{PR}).

Experimental data are gathered in graphs of figure 6 where, for every tested $F_{n\nabla}$, R_T/Δ variations in percent are shown, as regards starting condition without intruder nor flaps at $\vartheta=0°$. In the same figure dynamic trim angles in degrees are represented versus flaps angle or intruder protrusion S_i/L_{PR} (upper curves).

It is evident that intruder is more efficacious than flaps. It is useful to underline that protrusions of intruder are always lower than 20 mm for full scale ships, value over that a high decrease of performances is generally found.
At $F_{n\nabla}=2.15$ flaps use improves hull performances, up to about 5% at their maximum testable angle of incidence that is 8 degrees. At the same Volumetric Froude Number improvement caused by intruder is about 17%. With model trim by stern ($\vartheta= 1.15°$) intruder efficacy produces the maximum resistance reduction – about 20% - but not at the maximum intruder protrusion. As a matter of fact, if S_i/L_{PR} increases a little more R_T/Δ increases very much. It's interesting to notice that if the resistance decreases the dynamic trim angle generally decreases too: from 8°, of the starting common condition without flaps nor intruder, to 7° with flaps and to about 4° with intruder at minimum R_T/Δ.
At $F_{n\nabla}=2.80$ performances improve up to about 3% by flaps, whereas resistance decreases about 8.5% at $\vartheta=0°$ and about 7% at $\vartheta=1.15°$ by intruder, and the corresponding τ is 4°. Also in this condition is evident that if intruder protrusion keeps on increasing, resistance increases too.

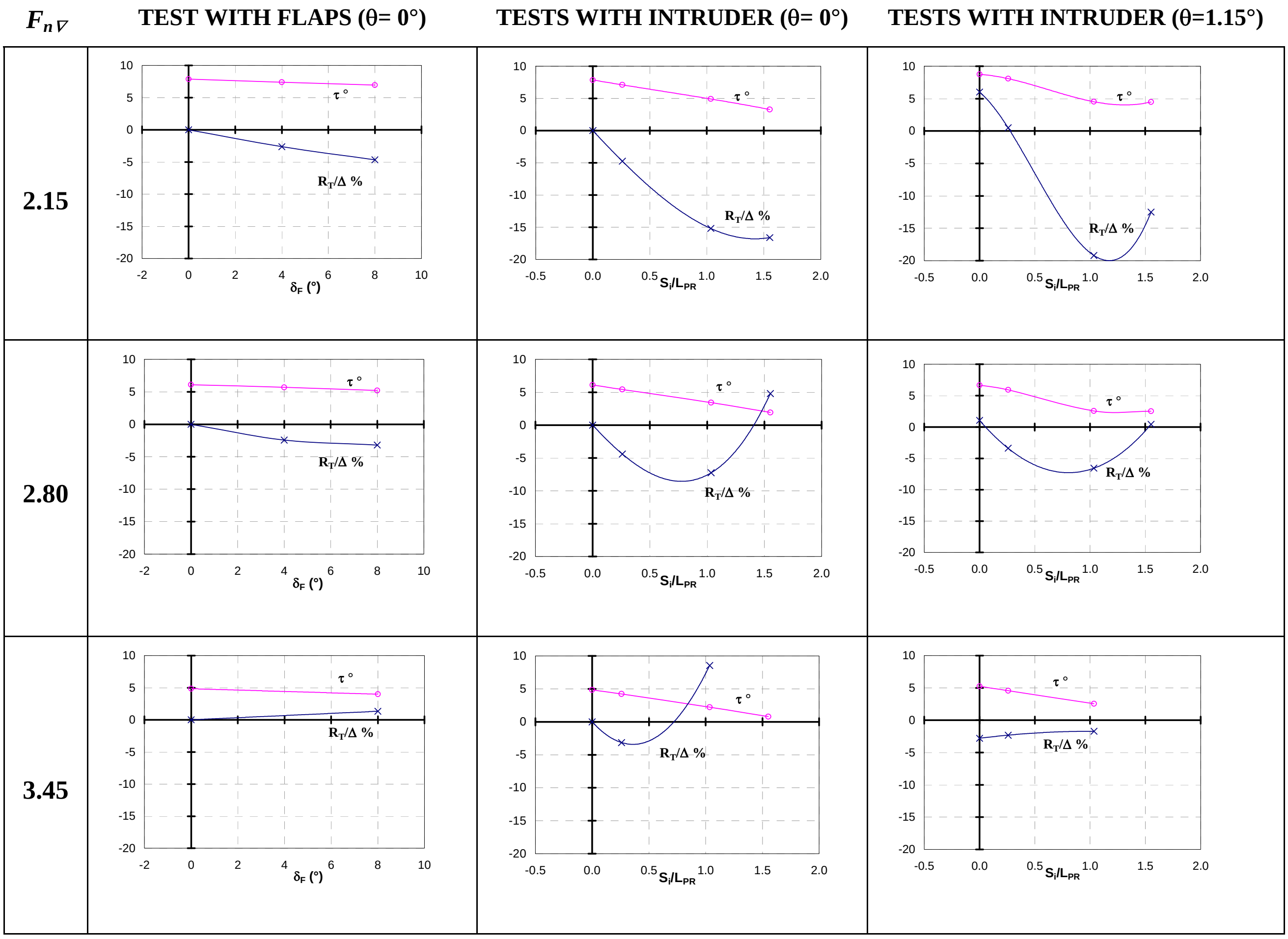

Figure 6: Model. A: Comparative tests flaps/intruder.

At $F_{n\nabla}=3.45$ a resistance worsening is obtained by flaps, whereas by intruder use, at $\vartheta=0°$, resistance decreases about 3%, and dynamic trim angle τ is 4° again. At $\vartheta=1.15°$ R_T/Δ reduction - about 2% - is anyway present because of trim by stern condition, and it persists even if there is a little intruder protrusion. Also in this case at minimum R_T/Δ dynamic trim angle is 4°. If protrusion increases τ still decreases but R_T/Δ increases.

5.2 DATA ANALYSIS

In graphs of figure 6 it is interesting to notice that τ about 4° - corresponding to the minimum R_T/Δ - is the angle of minimum resistance obtained by Savitsky for prismatic planing hulls [11] and in DTMB Systematic Series 62 [12] with similar geometrical characteristics. Besides it is appropriate to remark that the dynamic trim angles obtained by the model during the basin tests, because of not well-known reasons caused by scale effect, are generally higher than the corresponding full scale ship values [13].
Some graphs show that minimum resistance condition is verified at different S_i/L_{PR} values if $F_{n\nabla}$ changes.

On ships with large speed range, remote controlled mobile intruders are advantageous; they can be used like flaps to stabilize the boat and to improve performances. Plate protrusion – higher in pre-planning phase – must be reduced when the hump speed get near.

Photographs in figure 7 show the behaviour of the model at $F_{n\nabla}=3.45$ with $\vartheta=0°$. In the first one, without intruder, keel comes out from water at section 7 whereas in the second one, with $S_i/L_{PR}=0.26\times10^{-3}$ it comes out further on (at section 8), and the hull is more horizontal in comparison with the precedent condition. In this last case we have about the minimum resistance and the dynamic trim angle is 4°. The following photographs show tests with $S_i/L_{PR}=1.03\times10^{-3}$ and $S_i/L_{PR}=1.55\times10^{-3}$: because of the excessive protrusion, the point where keel comes out from water moves toward the bow, dynamic trim angle decreases and waves are higher and more visible. The result is a quick increase of resistance for a decrease of the dynamic trim angle in comparison with its optimum value, phenomenon already pointed out by studies on planing prismatic hulls [11] and by systematic series [12].

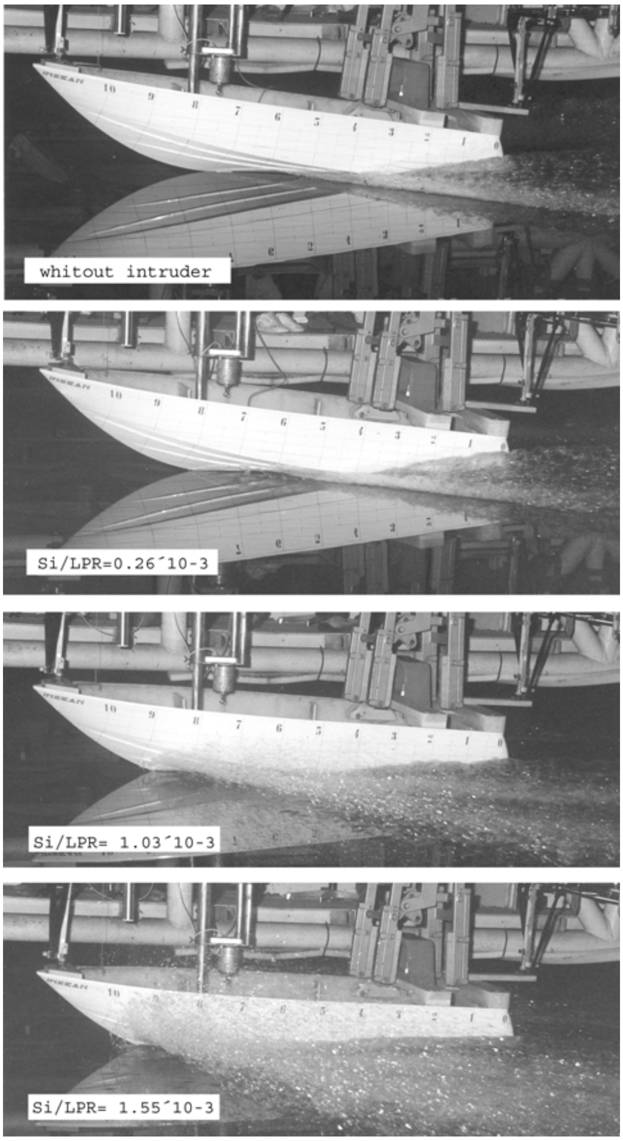

Figure 7: Differences of behaviour of mod A at $F_{n\nabla}=3.45$, $\vartheta=0°$ with and without intruder.

6. CONCLUSIONS

By tests performed at Insean on three different models is clear that intruder can induce significant changes of dynamic trim angle and can lift the stern. These changes can reduce waves and then hull resistance. On the other hand an excessive protrusion, or it's use if not necessary, can strongly increase resistance.
Besides:

- Fixed intruder is useful above all on big planing and semi-planing hulls, generally the ones with high L_{PR}/B_{PX} (≥4) or the ones which navigate at Volumetric Froude Numbers lower than 2.5 (hulls that never navigate completely planing). In these cases intruder is useful to correct a too high trim by stern, which sometimes is characteristic for this kind of boats that tend "to sit on wave" they produce. It's installation on these hulls is very cheap because it consists of a plain plate positioned under the transom jutting out just a few millimetres. Experimental results have shown a resistance reduction even more than 20%. Protrusion must be carefully chosen by practical tests.
- Mobile intruder is more recommended for ships with a larger speed range, ($F_{n\nabla}>2\text{-}2.5$). In these cases in fact as speed gets near the hump one, plate protrusion has to be shortened, because intruder reduces dynamic trim angle too much. On these boats, that typically have low L/B ratios, is often enough to install commercial devices, even if they have a partial length in comparison with the transom one.
- Intruder is useful to correct the behaviour of a boat that navigates trimmed by stern too much and to improve it's performances. Moreover experimental tests have shown that – in these cases – the efficacy of this device increases and it is valid on a larger speed range. Therefore, if intruder is used, can sometimes be useful to trim by stern statically the boat.
- By experimental data analysis intruder is generally more efficacious than flaps, both as regards improvement of performances and as regards the larger functioning speed range. In fact to obtain by flaps an effect as intruder one – with respect to dynamic stern support and to improve the trim – big flaps with high angles of incidence are indispensable, but they cause a high resistance increase and reduce - till they undo them – the advantages produced by themselves. By intruder, instead, a few millimetres protrusion is enough to obtain the same dynamic effects, against a negligible added resistance because it completely works in the boundary layer.
- Matched devices intruder/flap have been already tested and they are spreading, with intruder placed downstream flaps on their trailing edge or upstream. In this last case practically flaps are not coplanar with the bottom but they are a few millimetres lower. [14]. If the two devices are joined, to balance their characteristics very well is necessary.

The rapid spreading of intruder, caused by it's cheapness and it's simple installation and use, is giving rise to some changes of it's morphology, and then of it's working, to adapt it to particular hull forms or appendages and/or to existing flaps. Therefore further studies and tests are useful and desirable to advise planners and market about the working and the potential of this device, as well as about it's correct installation.

7. REFERENCES

1. LIEBECK, R.H., 'Design of Subsonic Airfoils for High Lift', *Journal of Aircraft, Vol.15, No. 9*, September 1978.
2. STORMS, B.L., JANG, C.S., 'Lift Enhancement of an Airfoil Using a Gurney Flap and Vortex Generators', *Journal of Aircraft, Vol. 31, No. 3*, June 1994.

3. JEFFREY, D., ZHANG, X. and HURST, D.W., 'Aerodynamics of Gurney Flaps on a Single-Element High-Lift Wing', *Journal of Aircraft, Vol. 37, No.2*, 2000.
4. ZERIHAN, J., ZHANG, X., 'Aerodynamics of Gurney Flaps on a Wing in Ground Effect', *AIAA Journal, Vol. 39, No.5*, May 2001.
5. KATZ, J., LARGMAN, R., 'Effect of 90 degree flap on the aerodynamics of a two element airfoil', Journal of Fluids Engineering, 111:93-4, 1989.
6. PROUTY, R.W., 'Aerodynamics'", *Aviation today - Rotor & wing,* October 2003.
7. ROESCH, P., VUILLET, A., 'New designs for improved aerodynamic stability on recent Aerospatiale helicopters', Proceeding of the 37th Annual Forum, American Helicopter Soc., 1981.
8. IX ITTC, 'Ninth International Towing Tank Conference – Proceedings', Paris 1960.
9. SEWALL, W.G., MCPHEE, R.J. and FERRIS, J.C., 'Wind tunnel test results of airfoil modifications for the EA-6B', *AIAA Paper 87-2359*, August 1987.
10. VIII ITTC, 'Eight International Towing Tank Conference', Madrid 1957.
11. SAVITSKY, D., 'Hydrodynamic Design of Planing Hulls', *Marine Tecnology*, 1964.
12. CLEMENT, E.P., BLOUNT, D.L., 'Resistance Tests of a Systematic Series of Planing Hull Forms', *Transaction SNAME, Vol. 71, pp. 491-579*, 1963.
13. PENSA, C., 'La Sperimentazione in Vasca Navale delle Imbarcazioni da Diporto', *SEA-MED 2004, Messina*, July 2004.
14. TSAI, J.F., HWANG, J.L., CHOU, S.K., 'Study on the Compound Effect of Interceptor with Stern Flap for two Fast Monohulls with Transom Stern'. *FAST 2003, Ischia (Italy),* October 2003.

8. AUTHORS BIOGRAFY

Andrea Mancini and **Alessandro Moriconi** hold the current position of experimental technicians at Insean, the Italian Ship Model Basin. Their previous experience includes resistance, self-propulsion and sea-keeping tests on a lot of types of hulls, such as ferry boats, catamarans, planing and semi-planing ships, motorboats, IACC yachts etc.