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ORIGINAL PAPER

Methodology to study the comfort implementation for a new generation of hydrofoils

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Abstract

Among the high speed crafts to be used as ferries, hydrofoils are considered the best solution to obtain high speeds and to reduce ship motions with the consequent comfort for passengers; in fact as long as the wave heights allow the hydrofoils to fly above the sea level the floating hulls are not effected by the sea conditions. It is important to underline that, in order to achieve the required performances, the construction techniques must be carefully controlled and refined because there are also some structural problems to be faced and solved to obtain a weight reduction. This study shows the results of a complete series of test, in towing tank and at sea, performed by the authors on a new class of hydrofoils designed and built by an Italian line. This research refers, in particular, to the fleet of The Liberty Lines, as they are the most important operators in the world for passenger hydrofoils, with more than 30 units, constantly updating them and recently developing a brand with a new series of semi submerged wings to face the typical defects characterizing this type of naval unit.) where fundamental points have been analyzed such as: the wing hydrodynamic optimization by means of model testing; the structural study of new wing systems and the update of the production processes with new construction techniques, and the improvement of the passengers comfort as for accelerations and vibrations. The tests have demonstrated a significant gain for new projects.

Keywords Hydrofoils · Self propulsion test · Wing design · Seakeeping · Comfort

1 Introduction

This target has been chosen because the seakeeping qualities of hydrofoils, compared to other types of units with the same displacement, remain undisputed as already well shown in the literature of the sector [1].

The constant adoption of the last technological advancements in the field of materials, production processes and applications as for the design aid has made possible to renew, update and improve this class of units, limiting or even completely solving the defects and limitations of hydrofoils for commercial use.

The present article wants to focus on the aspects related to the design and construction of the supporting wings, and finally to introduce a comparison between traditional hydrofoils (RHS-160) and an innovative project named the HF01 project. This comparison is developed and certified trough tank tests and accelerations obtained during sea trials.

The HF01 is the new hydrofoil studied to replace the previous model RHS 160. (The differences will be herewith examined) The HF-01 shows a completely different concept from the RHS 160. It is not simply an optimization, because it has a completely different wing profile, a different technology for the wing construction and realization of structure which are completely welded and without rivets. It is obvious that the General arrangement can be similar, due to the need to cope with similar needs for passengers and lines operating from Sicily and the main isles around.

The HF-O1 project target aim project was to solve most of the problems regarding the traditional construction of hydrofoils and to improve their performances (Fig. 1).

The RHS-160 was a conventional hydrofoil, constantly optimized through the years but still using traditional solutions for the construction of wings and structures (Fig. 2).

The main characteristics of the 2 series are shown below (Table 1).

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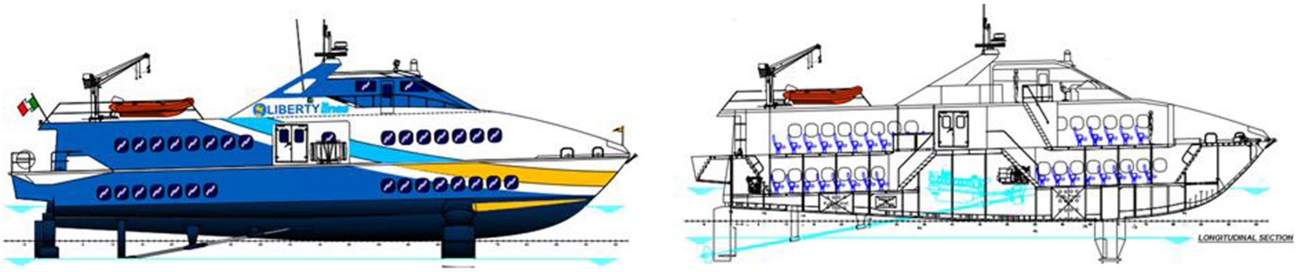

Fig. 1 A The HF01 hydrofoil

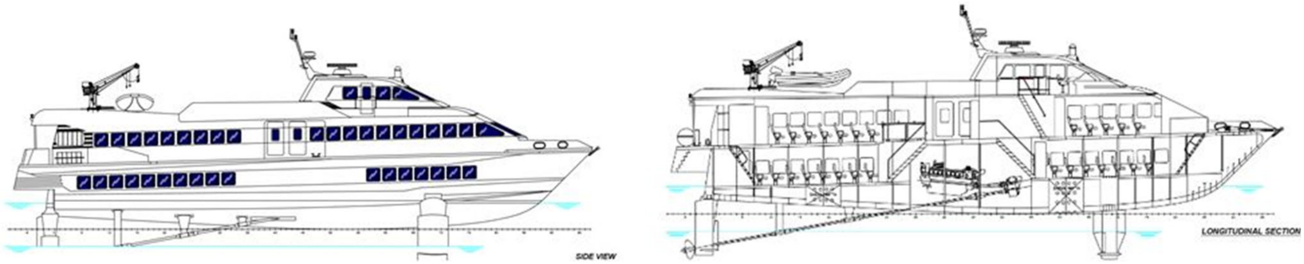

Fig. 2 The traditional RHS 160

Table 1 Main dimension of hydrofoils

	RHS-160	HS-01
Overall length (m)	31.20	31.70
Width outside the frame (m)	6.70	6.80
Maximum immersion (m)	4.20	4.20
Distance between the wings (m)	20.98	20.95
Passenger capacity	212	235
Maximum speed (kn)	35	35
Engines (kW)	2 × 2000	2 × 2000

2 Construction system of RHS-160

The wing configuration is of the “Avion” typ, i.e. about 70% of the weight of the unit, during the flight phase, is supported by the lift of the forward wing. The shaft line, more than 15 meters long, starts from the engine positioned at about half length of the ship up to the aft wing where the central flow plate acts as a support. The long axis line, where for most of its length operates outside the frame, is supported by three orders of “V” arms (Fig. 3).

The wings of this type of unit are secant (semi submerged) with a polygonal shape, characterized by wing profiles of the NACA family with thickness distribution “16” and median line “65”.

In order to increase the lift at taking off and as an aid to electronic stabilization, the flaps are moved by integrated feedback hydraulic actuators.

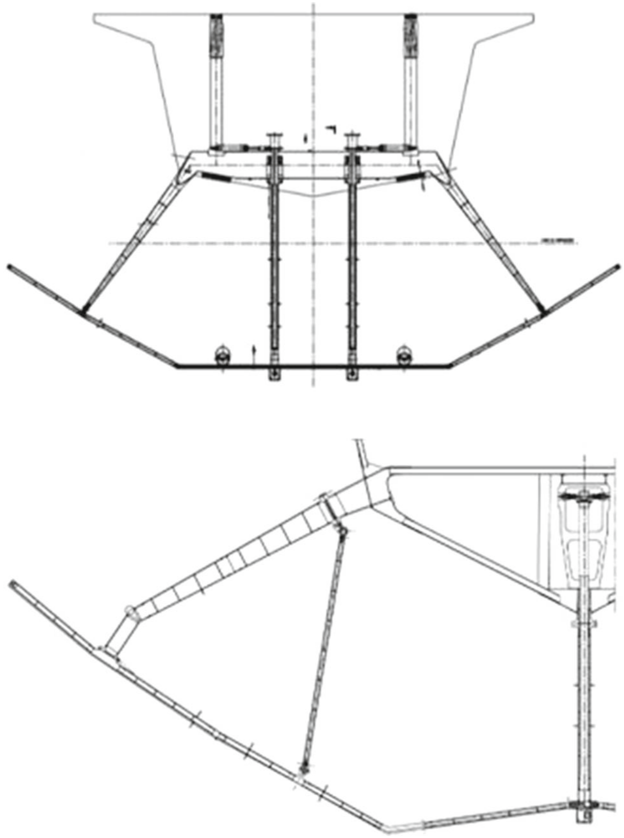

Fig. 3 Fore and aft wing system

The constructive system is a traditional fairing type, and is characterized by a structure composed of frames, longitudinal stiffeners and shell plates, welded in every part.

Fig. 4 Picture of fore wing and structure

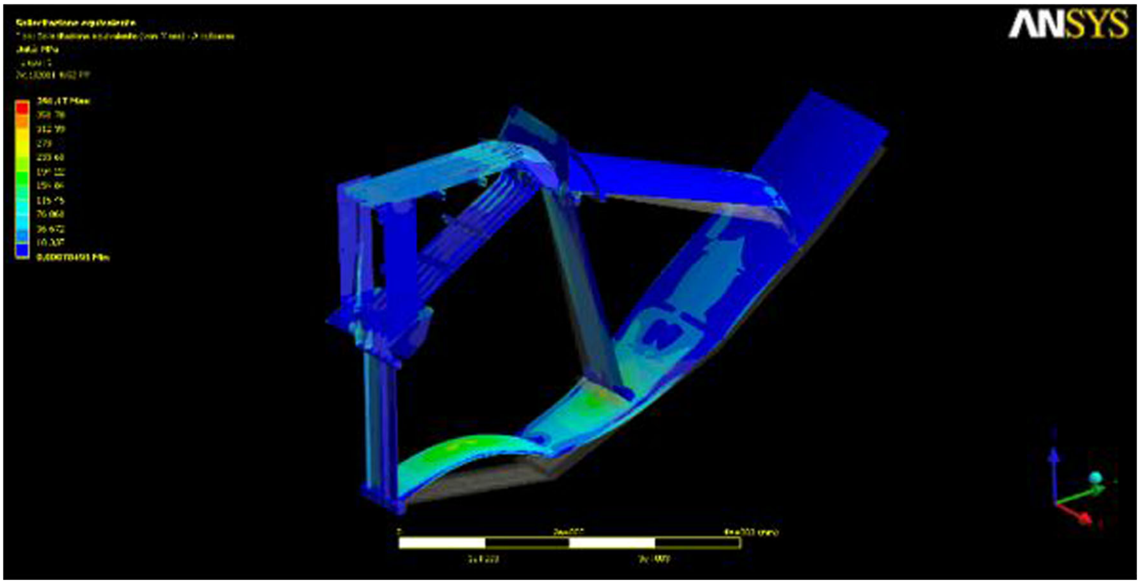

Fig. 5 FEM–CFD model for optimization of wing of HF01

The material used is a semi-structural structural steel designated with the abbreviation S460 with an yield strength of 460 MPa.

The limits of this construction are related to the construction of the wing profiles, in fact the technique used does not allow to obtain profiles with complex shapes and therefore it has got a range of decidedly limited solutions.

The used steel, suitable to be hand-crafted, and the thermal stress that the structure undergoes, due to the intense welding cycle, causes the wing assembly not to be suitable to work under an intense load of fatigue, generating periodically and repeatedly structural failures in areas of the greatest concentration of stresses.

Summarizing, the weaknesses of this type of unit are the following:

- Breaking fatigues of the wings
- Expensive constructive process of the wings
- Simple wing profiles with low performances

Furthermore the technology of construction of the riveted aluminum hull gives origin to several problems as for

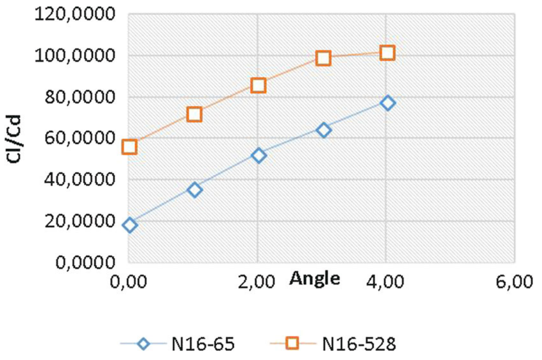

Fig. 6 Traditional versus new internal wing profile coefficients

Table 2 JONSWAP y = 3.3 wave spectra for seakeeping test

Sea state (–)	Hw 1/3 (m)	Tp (S)
3	1.08	4.00
3	1.25	4.00

high production costs, high maintenance costs, infiltration of water and vibrations (Fig. 4).

3 The project HF01

The idea for the project HF01 was to use a different technology for the wings and the hull structure, with a much more massive usage of welding, despite the very limited thickness of elements.

In particular, as for the realization of the wings, the framed solution for a wing realized from a plenum of metal, with a different profile, and consequentially different geometric ratios, was given up in order to solve or reduce the above mentioned problems.

The hydrodynamics of the new wings was optimized in a succession of steps, starting from CFD optimization, then with resistance tests at MARIN, with sea keeping tests at SVA in Wien, and finally with a series of sea trials where the vibration on structure was measured during a navigation on the same route, on the same day, in the same sea, on a traditional RHS 160 and on a new HF01.

3.1 Optimization of the wing profile

The optimization of the wing profile must be based on the necessity of reaching the best the lift/resistance ratio avoiding cavitation.

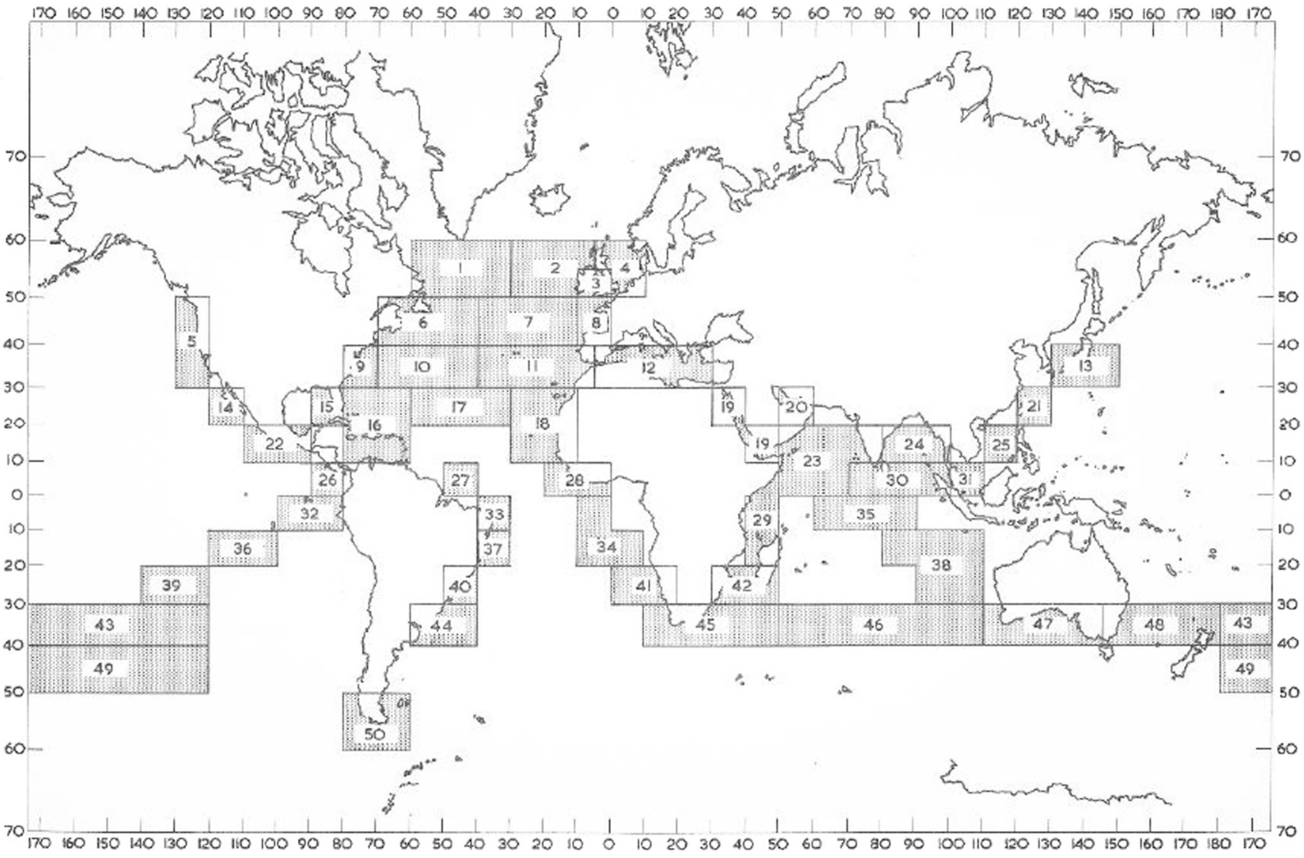

Fig. 7 Marsden square subdivision

Fig. 8 Seakeeping test of RHS 160 at SVA in Wien

Fig. 9 Seakeeping test of HF01 at SVA in Wien

As well known, the cavitation on a wing profile is influenced by the thickness distribution and by the variation of the "t/c" = thickness-rope ratio together with the "f/c" = buckle-rope along the wingspan.

The problem is that, even if the CFD simulation can give the best distribution for the f/c and the t/c ratios, these ratios must be obtained from the carpentry of the wing, giving to the wing the necessary strength to operate.

For this reason new technologies have been studied and developed on order to realize the HF01 wings, because a reduction of the t/c ratio can reduce the frictional resistance, but using the framed construction for the wing there is a limit given by the need of welding the frames. This limit is extremely tight considering a thickness of the wing for a 35 m. hydrofoil, in the range of 60–70 mm.

This aspect, that is the thickness of the wing, is related to the fact that, considering the average chord length and the surface roughness, the boundary layer is in turbulent regime for most of the length of the wing profile. The viscous resistance of the profile is for the most part governed by the thickness ratio and its distribution. The higher the thickness, the higher the form factor, consequently the frictional resistance increases.

The analysis of the profile has been performed to optimize the coefficient of the profile (Fig. 5).

The reduction in the t/c ratio reduces the resistance, but increases the negative pressure peak caused by the variation of incidence during the take-off phase, making the profile and consequently the whole wing more vulnerable to cavitation, a phenomenon that must be limited as much as possible and

Table 3 Power gain in calm water

	Mod. 2741-1 (HF-01) Test n.33368 + 99				Mod. 2741-2 (RHS-160) Test n.33372			
Vs (kn)	R_{TM} (kp)	Δ R_{TM} (%)	P_{ES} (kW)	Δ P_{ES} (%)	R_{TM} (kp)	Δ R_{TM} (%)	P_{ES} (kW)	Δ P_{ES} (%)
28.0	7.46	–	1702	–	8.56	14.67	1979	16.24
30.0	7.22	–	1737	–	8.17	13.15	1993	14.70
32.0	6.97	.	1759	–	7.81	12.06	2001	13.72

Table 4 Power gain in waves

			2741-1 Test n.33368 + 99				2741-2 Test n.33372			
H_W 1/3 (m)	T_P (S)	V_S (kn)	R_{TM} (kp)	Δ R_{TM} (%)	P_{ES} (kW)	Δ P_{ES} (%)	R_{TM} (kp)	Δ R_{TM} (%)	P_{ES} (kW)	Δ P_{ES} (%)
1.25	4.0	30.0	7.28	–	1954	–	8.30	14.07	2229	14.10
1.08	4.0	32.0	7.13	–	2046	–	8.09	13.53	2317	13.25

Table 5 Acceleration in waves

	2741-1 Test n.33368 + 99			2741-2 Test n.33372					
Vs (kn)	Acc.1 (g)	Acc.2 (g)	Acc.3 (g)	Acc.1 (g)	Acc.2 (g)	Acc.3 (g)	ΔAcc.1 (%)	ΔAcc.2 (%)	ΔAcc.3 (%)
30.0	0.070	0.069	0.171	0.076	0.075	0.175	8.68	8.99	2.62
32.0	0.090	0.061	0.160	0.091	0.074	0.179	0.55	21.53	12.25

Table 6 General operability limiting criteria for ship (NORDFORSK 1987)

	Merchant ship	Naval vessels	Fast small crafts
Vertical acceleration at forward perpendicular (RMS)	0.275 g (L ≤ 100 m) 0.05 g (L ≥ 330 m)	0.275 g	0.65 g
Vertical acceleration at bridge (RMS)	0.15 g	0.2 g	0.275 g
Lateral acceleration at bridge (RMS)	0.12 g	0.1 g	0.1 g
Roll (RMS)	6.0°	4.0°	4.0°

Table 7 Criteria with regard to acceleration and roll (RMS) (NORDFORSK 1987)

	Vertical acceleration (RMS)	Lateral acceleration (RMS)	Roll (RMS)
Light manual work	0.20 g	0.10 g	6.0°
Heavy manual work	0.15 g	0.07 g	4.0°
Intellectual work	0.10 g	0.05 g	3.0°
Transit passengers	0.05 g	0.04 g	2.5°
Cruise liner	0.02 g	0.03 g	2.0°

totally absent in some areas of the wings. The second consequence, just as important as cavitation, is the one related to strength as, because of the high Cl, a thinner profile would lead to problems of structural collapse.

The following images show a comparison among the traditional wing profiles historically used in the field of secant wing hydrofoils and the wing profile selected by the optimization process (Fig. 6).

The new profile, N16-528 has showed a significant advantage, and it has been adopted, taking as consequence the need of using new technologies to realize the wing.

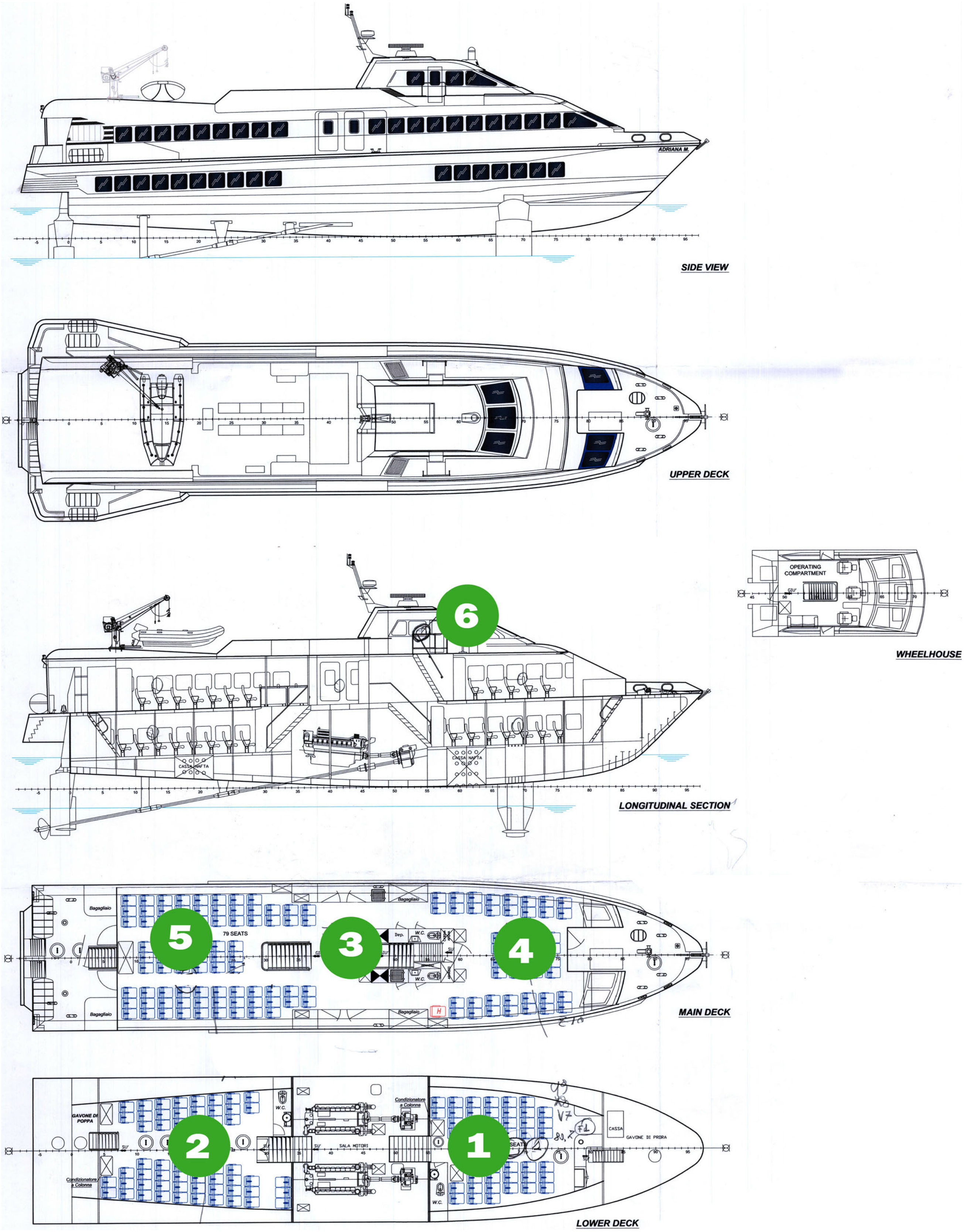

Fig. 10 Noise and vibration points of measurements on HF-01

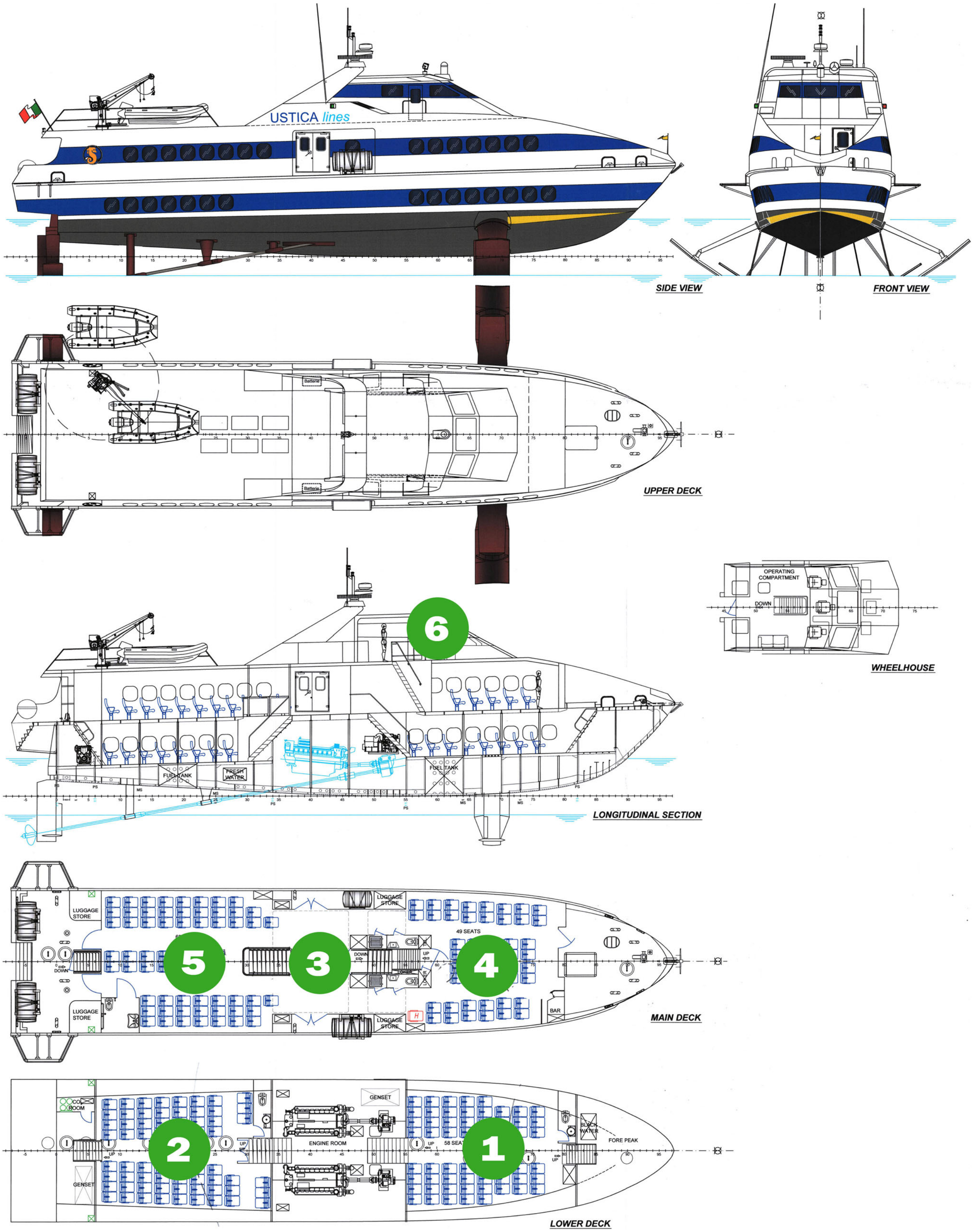

Fig. 11 Noise and vibration points of measurements on RHS-160

Table 8 Criteria with regard to acceleration and roll (RMS) (NORDFORSK,1987)

	1 Fore—lower deck	2 Aft lower deck	3 Boarding main deck	4 Fore main deck	5 Aft aain deck	6 Wheelhouse
HF-01	83 db	77.8 db	79.6 db	73.5 db	71 db	69.9 db
RHS-160	80.7 db	82.3 db	79.4 db	74.6 db	76.9 db	72.1 db

Table 9 Vibration measurements (Cruise speed 30 kn)

Position	Test n.	HF-01 (mm/s)	RHS-160 (mm/s)
1-Fore lower deck	008	1.9	1.9
	009	1	3.8
	007	1.1	5.5
2-Aft lower deck	014	1.7	1.4
	015	3.4	4.9
	013	3.2	8.4
3-Boarding area main deck	011	1.3	1.5
	012	1.8	2.2
	010	8.3	3.4
4-Fore main deck	020	0.7	1.8
	021	0.6	2
	019	3.2	4.5
5-Aft main deck	017	1.2	1.3
	018	3.1	2.9
	016	4.5	1.9
6-Wheelhouse	023	0.6	1.5
	024	3	1.5
	022	2.4	6.7

The weaknesses of this type of wing profiles relate exclusively to their geometric complexity, which is directly reflected in the real wing construction process.

In the last years new technologies were studied and developed to realize more performing wings profiles: the new wings are now realized by machining a plenum piece of steel, instead of using the technology of frames and plates.

This solution allowed to adopt the new optimized profiles.

4 Validation of the new profiles trough tests in model basin

Once defined the new profiles, the further step was to find a new methodology to evaluate them from the point view not only of the resistance but also of the seakeeping.

The new methodology adopted was planned to produce results comparable not only in the present time for the 2 projects chosen, but also to make possible, in future, to confront data from new constructions, making an evaluation of new parameters.

One of the main problem to solve was also the choice of parameters for to evaluate the absolute behavior, considering that hydrofoils are passenger unites, but different from traditionals, so the authors decided to follow as a guide line parameters for HSC crafts, and Nordfosk 1067, considering them valuable for the passengers of hydrofoils, even if the voyage is usually very short (20–30 min)

Aiming at this, a campaign of tank test at model basin were carried out, using two different models, in the same scale, one for the RHS-160 and one for the HF-01, with old and new types of wings, to compare the behavior of the wing system.

In order to compare the two solutions 'Resistance test' and 'Seakeeping test' were carried out at Vienna Model Basin (Schiffbautechnische Versuchsanstalt—SVA) and the measurement involved the differences in power and the vertical accelerations for the hull navigating in rough sea, with waves [2].

Obviously testing the hulls at tank test ensured the exact reproduction of the same wave spectrum, for both the models. The operational speed was chosen as of 30 and 32 kn, depending from the wave height, this was the assumed commercial speed, lower than the maximum speed of 35 knots, suitable in the sea state selected.

The wave spectrum was selected and a JONSWAP spectrum was chosen in consideration of the chosen operational area of these hydrofoils.

The wave spectra was selected considering the Marsden square subdivision (Fig. 7).

Finally, the wave spectrum chosen for the tests was defined as follows (Table 2; Figs. 8, 9).

At the SVA facilities the tests were performed in Summer 2017, the displacement of the 2 units was the same, corresponding at a full load of passengers and consumables, corresponding at 135 t.

The models were realized with appendages such as shaft lines and rudders, with adjustable flaps. To have comparable data the tests have been performed with 0 angle of flaps for both models.

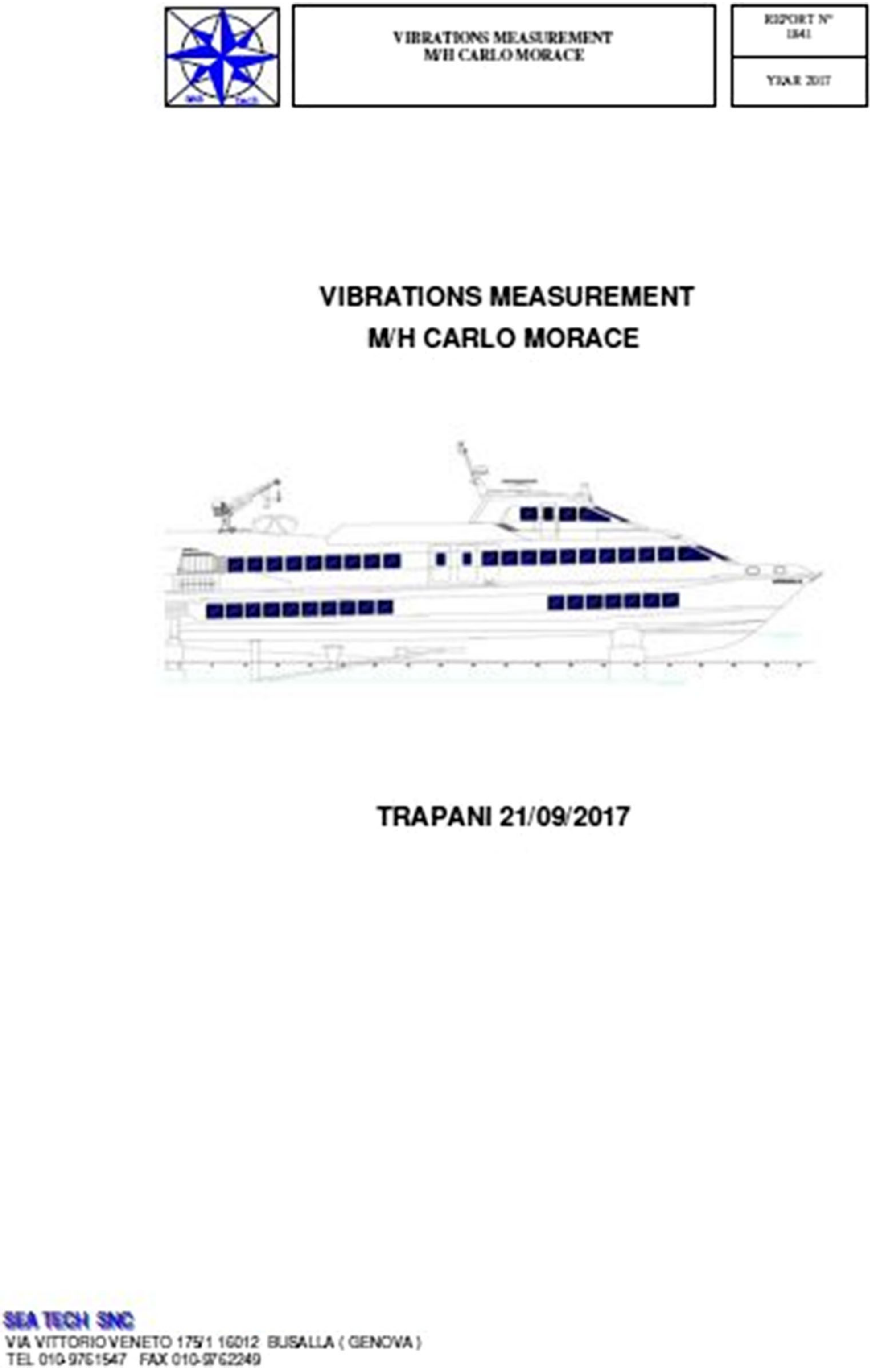

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Fig. 12 Cover of report for vibrations measurement

The first step of testing was to measure resistance in the speed range from 28 to 32 kn, to verify if the new geometry of the wings was giving results.

The test comparison showed a significant advantage of HF01, with an average gain of 14% (Tables 3, 4, 5).

After the resistance tests, a new set was carried out, applying the Wave spectrum already described, with a Speed of 30 knots for waves of H_W 1/3 = 1.25 (m) and 32 knots for waves of H_W 1/3 = 1.08.

Each one of the two models was equipped with accelerometers in order to measure the accelerations in three different points, to obtain data to be compared with the standard mentioned in the main literature for the comfort of passengers of ships (Tables 5, 6) [3, 4].

To summarize it can be confirmed that, compared to the design solution of the RHS-160F, the new wing system offers advantageous solutions in terms of performance in calm seas and in rough seas (Tables 6, 7) [5, 6].

Examining the above tables with the referring values, it is possible to see that the values of the HF-01 hydrofoils are in average lower than 0.15 g, considered an acceptable value for merchant ships, where the time of presence on board is longer than the average voyage of hydrofoils (about 30 min.).

5 Sea trials

After the positive results of the tank test investigation, in order to have a complete set of measurements, a set of tests was planned during the navigation two hydrofoils, one RHS-160 built using the traditional technology and a new HF01, with measurements of noise and vibrations, to verify that the advantage showed in model basin was also in real conditions.

A company specialized in measurements of noise and vibration, the Sea Tech Snc., who produces reports accepted by the Class registers for the Comfort certificates, was appointed to perform tests with instruments validated and certified.

For the noise: Bruel & Kjaer—B&K 2270 with microphone B&K 4189
For vibrations/accelerations: Bruel & Kjaer—Vibrationsmeter 2270
Accelerometer PCB Type 308
Accelerometer calibrator mod. 4291
Software B&K mod. BZ 5503

This is the way the test was planned: on the same route, in the same day, at the same speed, in the same sea conditions, a measurement of vibrations and noise was performed in a selected number of positions.

The route was navigated in the same direction at few minutes of distance between the passages.

The positions of measurement points were chosen similar i.e.: center of passenger fore saloon, center of wheelhouse and so on in order to have comparable results (Figs. 10, 11).

The results from the test, as already done for the tank tests, were compared with the main data available in literature for the comfort onboard fast boat, and it is possible to see the advantage of the new construction (Table 8).

The noise measurements showed a general significative improvement of the new construction, with noise values lower or equal.

As already explained, but wanting to define a methodology to be used for new futures units, the measured noise values were compared with the values reported in Rules for HSC; for reference the authors considered the Norske Veritas Rules for HSC: *Ship Rules Noise and Vibration for Ship 2014.*

In the same conditions and at same time of noise measurements, vibration measurements were performed, recording the values of accelerations along the three axis X, Y, Z (Table 9).

The vibration measurements, expressed in term of vertical accelerations, show a significative advantage for the new construction HF-01 with positive influence on passengers' comfort.

It is also important to underline that the structure of hydrofoils is extremely light, with a careful optimization to save material where unnecessary and consequentially in order to save weight [7]. So the reduction of vibration assumes great importance also in the expected lifetime of the structures (Fig. 12).

6 Conclusions

The results of the works show the progress made in the design of hydrofoils, the test at model basin shows a gain of 8% in vertical accelerations and 14% in resistance.

The tests at sea trial show a gain in vibrations and noise for the new construction HF 01.

So, finally, it is possible to summarize that the use of a new design for wings, with smaller f/c ratios, made possible by the realization of the wings from a plenum piece of steel manufactured with CAM system, allows the achievement of important increases in performance as for resistance and sea keeping [8] and simultaneously to solve some of the typical problems of stress resistance for materials and structures.

The Company, who supported financially the test and the research, and the Authors, are now studying new solutions to improve even more the efficiency of the wing system.

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