Genetic Optimization for Yacht Design

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ABSTRACT

This paper introduces a procedure for using genetic multi-objective optimization in yacht design. The problem described consists on the optimization of a bulb shape to improve the performance of the yacht. The two objectives considered are the minimization of the drag in calm water together with the minimization of the Vertical Center of Gravity (VCG), all the configurations should satisfy length and volume constraints. Since there is no a single optimum to be found, the MOGA-II was used as multi-objective genetic algorithm. The optimization of the bulb was obtained employing a parametric model, performing flow analysis and using a multiobjective optimization software. The distributed optimization search exploited the parallelization capabilities of the MOGA-II algorithm which allowed the evaluation of several designs configurations by running concurrent threads of the flow analysis solver.

Three bulb shapes of different length are selected between the non-dominated solutions. Using these three solutions, seakeeping tests of a fully appended scale model have been carried out at the towing tank of the University of Trieste. A single hull has been tested for each bulb configurations to check the influence of the bulb shape on the performance of the yacht in waves.

The results obtained are very satisfactory, and the procedure described can be applied to even more complex yacht design problems.

Categories and Subject Descriptors

J.6 [**COMPUTER-AIDED ENGINEERING**]: *Computer-aided design (CAD).*

General Terms

Algorithms,Design.

Keywords

Yacht Design, Multiobjective Optimization.

1. INTRODUCTION

Last Louis Vuitton Cup and XXXI America's Cup revealed that while the hull shapes were strongly similar for all the top teams' boats, the bulb shapes were quite different, even if boat performances were very close one to each other.

XXXII America's Cup will adopt Version 5 of AC Rule, which is more restrictive than Version 4 as far as the hull shape, leaving the same degree of freedom to the design of appendages, so the bulb shape optimization will become an even more significant task in the development of a winning yacht.

Currently CFD gives the way to lower the number of real life trial and error experiments. It is used to study the flow field of different geometries, giving results on the best one. What if we want to get the optimized solutions? In some cases, this is straight to obtain, we only need a few (less than 10) iterations. However, when the system gets more complex, the use of optimization software is required. The use of modern Computational Fluid Dynamics (CFD) codes coupled with automatic process integration and optimization tools allow us to explore the design space by evaluating a large number of design variations in a fast and smart way.

To improve the performance of an America's Cup yacht is important to consider not only the drag forces, but also the motions in waves and the related total mean resistance, considering that the location has changed and the weather/sea conditions are different from the Hauraki Gulf.

In this work seakeeping tests of an IACC fully appended scale model have been carried out at the towing tank of the University of Trieste. The model has been tested in head waves, with wave lengths that match the encounter frequencies at Valencia site in upwind sailing conditions, calculated with a heading angle of 150 degrees.

Three bulb shapes of different length have been designed using an automatic optimization procedure that, for each length chosen, minimizes the drag in calm water of the bulb and gives the lowest Vertical Center of Gravity (VCG). These bulbs have been used during the seakeeping tests to check the influence of their shape, mostly the length and related mass and added inertia, on the performance of the vertical motions of the yacht in waves.

The paper is laid out as follows: we first give a brief description of the tools and algorithms used for the optimization in calm water conditions of underwater appendages of the yacht using CFD coupled with CAD systems and mesh generators. After that we briefly describe the wave condition at Valencia site and the procedure to scale them in the model basin. Finally, we focus the attention on the experimental tests of the IACC yacht in head waves, with a description of the model and measurement set-up and with comments on the results.

2. PROBLEM DESCRIPTION

The design of an IACC yacht must comply with the class rules which fix certain relationships between principal dimensions of the yacht. There are no particular restrictions for the bulb shape according to these rules. In this work the weight of the bulb was kept fixed in order to maintain the boat's total displacement (note that the bulb represents 80% of the vessel's total displacement), and a length constraint has been was applied.

The analysis and optimization of underwater appendages of a racing yacht using Computational Fluid Dynamics (CFD) is a complex task that requires the integration of CAD systems, mesh generators and CFD codes. In this work the geometry was constructed using the commercial Computer Aided Design (CAD) tool Catia v5, where 20 parameters were used to define the bulb shape. The commercial mesh generation program, ICEMCFD[1] was used to mesh the fluid domain and the commercial CFD software CFX10[2] to solve the flow field around the bulb. The processes were integrated in modeFRONTIER[3], a commercial optimization software, which was also used to improve the performance of the entire boat.

The objectives of the optimization were to minimize the drag and to keep the center of gravity as low as possible, in order to decrease resistance and increase stability. Each design evaluation consists of three phases: modification of geometry, automatic grid generation and a CFD analysis.

2.1 Parameterization Strategy

The bulb shape was defined by a set of 20 parameters. The bulb parameterization was based on the modification of the three main curves of an ellipsoid: the top, bottom and side profiles are modified by adding Bezier curves defined by a set of control points (see figure 1). The coordinates of these points are the free parameters of the optimization.

The sections of the bulb were created starting from the intersections of the profiles with principal construction planes. Next a lofted surface of the bulb was created, and the geometry scaled to reach the target volume. The resulting length was constrained during the optimization process.

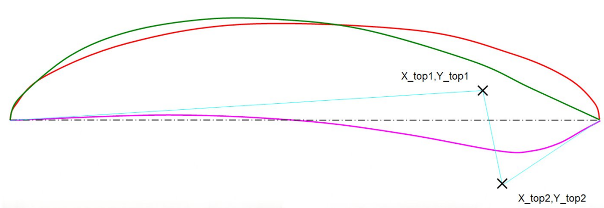

Figure 1. Ellipsoid top profile modification using a Bezier curve

2.2 Mesh Generation

The batch creation of a mesh is a two-step process: first, ICEM CFD is run in interactive mode to manually generate an automatic mesh from a prototype design. During this phase all the operations performed are recorded and then saved into a file (the macro file).

Subsequently, a generic bulb geometry model, saved over the prototype model (i.e., under the same directory, and with the same file name) can be meshed by having ICEM CFD run, in batch mode, the macro file previously recorded.

The mesh is a 2 Million hexahedral cells mesh (see figure 2).

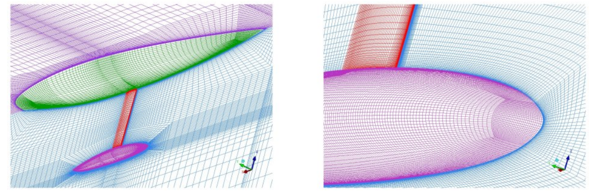

Figure 2. Hexahedral mesh used for the flow simulations

2.3 CFD Analysis

The batch creation of a mesh is a two-step process: first, ICEM CFD was run manually to generate an automatic mesh from a prototype design. During this phase all the operations performed were recorded and saved to a file (the macro file).

Then for every design iteration the parameters were modified by modeFRONTIER, which invoked Catia v5 to change the shape of the bulb, and ICEM CFD to mesh the modified design using the macro file created in the first phase.

The mesh created consisted of 2 million hexahedral cells.

3. OPTIMIZATION PHASE

The optimization was carried out using modeFRONTIER. The different components in the workflow define each of the stages in the automated optimization process: the input variables, the objectives, the optimization loop settings, including the scripts and macro to run the applications involved, the initial points and the optimization algorithm.

The actual Workflow is shown in figure 3. It has seventeen input variables that represent the degree of freedom of the bulb geometry. The discretization of each variable range from 13 to 71 steps.

The input variables were directly inserted in the Catia v5 model, where the model parameters were defined, so that changing the values of these input variables change accordingly the model parameters and therefore the shape of the model. The model was automatically exported in IGES format to be passed to ICEMcfd for the mesh process. VCG and length of the current bulb were directly extracted from the updated parametric model and stored in the output variables ("Zg_bulb" and "length"). The objective "min_Zg" was created using the output variable "Zg_bulb" and the constraint on the bulb length "length_constr" was created using the output variable "length".

modeFRONTIER ran ICEMcfd in batch in order to create the mesh of the CFD model (External Script node "icem" in Figure 5). The mesh file (transfer file node "mesh") was passed to the CFD preprocessor (External Script node "cfx5pre") and an automatic analysis and post-processing of the model was done running cfx5 solver (cfx5 solve) and cfx5 post processor (cfx5post) in batch mode. Analysis results were written into an ASCII output file (Output File node "bulb_001.out", see Figure 4). Results (viscous drag and pressure drag) were extracted from this output file and stored in the output variables ("drag_visc" and "drag_pres"). The objective "min_drag" was created using the two output variables “drag_visc” and “drag_pres” output variables.

In this study, we had two objectives:

- Minimize the drag.
- Minimize the VCG.

And one constraint:

- Minimum and Maximum length of the bulb

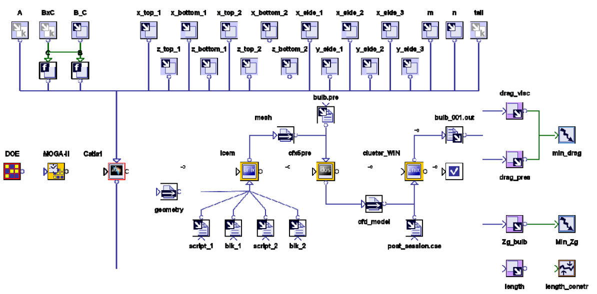

Figure 3. optimization Workflow

The problem was run on a remote 8 CPU Linux cluster. Since the concurrent run of threads of CFD solvers had to meet the license availability, python script was implemented in modeFRONTIER to perform the license polling as well as the concurrent execution of the CFD analyses for each design evaluation, thus maximizing the exploitation of the computational resources. Grid computing promises to deliver benefits by making use of all the available hardware resources. Grid technology [5] already showed its value in scientific research. More precisely, this technology allows reduction of CFD running time, by means of simultaneous computations on parallel hardware resources. As a result, large numbers of design configurations are computed in appreciably shorter time if compared with analogous tasks performed in traditional serial architectures.

Finally, given the multi-objective nature of the problem, a distributed and multi-objective genetic algorithm was selected in modeFRONTIER. Since several preliminary studies [6] showed no qualitative difference between the MOGA-II and other state-of-the-art methods in the forefront of multi-objective optimization (such as NSGA-II [7]) here we limited the study to MOGA-II. An in-depth description of MOGA-II is provided in the next section.

4. MOGA-II

The algorithm used was MOGA-II (Multi-objective genetic algorithm). MOGA-II is an improved version of MOGA (Multi-Objective Genetic Algorithm) of Poloni [8]. It uses a smart multi-search elitism for robustness and directional crossover for fast convergence. The efficiency of MOGA-II is controlled by its operators (classical crossover, directional crossover, mutation and selection) and by the use of elitism.

Elitism is very important in multi-objective optimization because it helps preserving the individuals that are closest to the Pareto front and the ones that have the best dispersion.

4.1 MOGA-II Results

MOGA-II was run with a population of 24 initial designs, evolving for 20 generations. The initial population was provided by the Sobol [10] method because of its capability of increasing the convergence of multi-objective genetic algorithms [11]. This type of sequence is called *quasi-random* sequence. That term is somewhat of a misnomer, since there is nothing random in this method. The points in this type of sequence are maximally avoiding of each other, so the initial population fills in a uniform manner the design space.

The following parameters were used: directional cross-over probability 50%, classical cross-over probability 35%, selection probability 5%, mutation 10%, elitism and steady evolution. When steady evolution is enabled, MOGA-II uses all the values as soon as they are available in a first-in first-out way guaranteeing the complete parallelization of the optimization process. The total number of evaluated designs was 480 over a period of time of 72 hours. Each single complete evaluation took an average of 40 minutes, the process was parallelized on 2 CPUs, four concurrent designs were run simultaneously.

Figure 4 shows the optimization results for the two objectives: drag and Vertical Center of Gravity. The chart clearly illustrates that the algorithm generates a well-spread set of non-dominated points. Unfortunately, due to the complexity of the problem, nothing can guarantee that this represents the true Pareto front. Anyhow, the robustness demonstrated by MOGA-II on several numerical tests gives us high hopes that, at least, these points represent a set of good solutions.

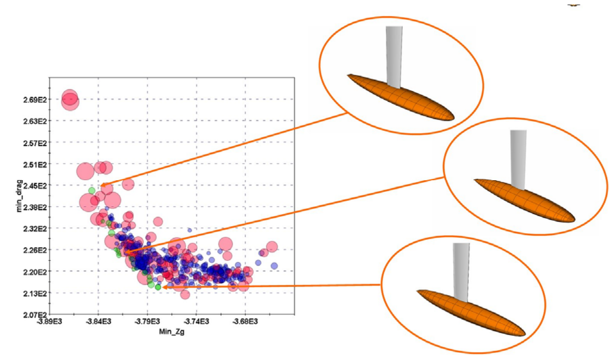

Figure 4 Bubble Chart : bubble radius represents constraint value, green bubbles are Pareto designs

Since there are more than one conflicting objective to be optimized simultaneously, there is no longer a single solution, but rather a whole set of possible solutions performing differently on the different objectives. Even though several solutions may exist only a limited set of them can be chosen and tested.

Three designs were chosen from the set of non-dominated solutions: the two extremes with minimum drag and lowest Vertical Center of Gravity, and the best trade-off according to the design requirements (see figure 4). The “best” trade-off design for each optimization was tested in the towing tank.
The final bulbs in model scale are shown in figure 5.

Figure 5: Bulb shapes tested

5. Analysis of wave data in Valencia race area.

The wave conditions reproduced in the towing tank for the experimental tests were defined using a database of statistical surveys of a buoy located near the Valencia race area. The Waverider buoy measures the free surface elevation and the data are analysed in order to give the significant wave height, peak period and mean direction. These data area available since 1985.

All data are accessible from a web page (ref: [4]) and are presented in tables (Wave Scatter Diagrams) as given in Table 1:

Table 1: Wave data at Valencia site

		T_p (s)											Tot
		≤ 1	2	3	4	5	6	7	8	9	10	>10	
H_s (m)	≤ 1.0	-	-	3.784	14.037	20.091	18.577	14.642	9.459	2.876	1.665	0.606	85.736
	2.0	-	-	-	0.151	0.908	2.611	2.800	2.611	1.324	1.249	1.022	12.675
	3.0	-	-	-	-	-	-	0.265	0.530	0.076	0.114	0.492	1.476
	4.0	-	-	-	-	-	-	-	-	-	0.076	0.038	0.113
	5.0	-	-	-	-	-	-	-	-	-	-	-	0.000
	6.0	-	-	-	-	-	-	-	-	-	-	-	0.000
	7.0	-	-	-	-	-	-	-	-	-	-	-	0.000
	8.0	-	-	-	-	-	-	-	-	-	-	-	0.000
	9.0	-	-	-	-	-	-	-	-	-	-	-	0.000
	10.0	-	-	-	-	-	-	-	-	-	-	-	0.000
	>10.0	-	-	-	-	-	-	-	-	-	-	-	0.000
Total		-	-	3.784	14.188	20.999	21.188	17.707	12.599	4.275	3.103	2.157	100%

Yearly statistical data were grouped in a table containing all surveys from 1985 to 2003. Data were plotted into two histograms: percentage of occurrence of significant height and percentage of occurrence of peak period (see figure 6).

Since next edition of Louis Vuitton Cup and America's Cup will be held from April to June 2007, tables and histograms of seasonal data were also produced.

The frequencies (and then the wave length) to be reproduced in the towing tank were defined from the analysis of survey data related to the period of interest. The histogram related to summer, America's Cup final, is particularly narrow from 3.5 to 6 seconds of peak period and has a maximum occurrence of 36% in the interval from 4 to 5 seconds. Considering spring months, the diagram is wider and percentages of occurrence are distributed in a more homogeneous way, with a broader peak of occurrence from 4 to 6 seconds.

Larger periods were excluded because, even if there are moderate percentages of occurrence in the first period of the event, they are unlikely during the final phase of Louis Vuitton Cup and America's Cup Matches.

The range of frequencies chosen is the range that corresponds to the peak periods from 3.5 to 6.5 seconds.

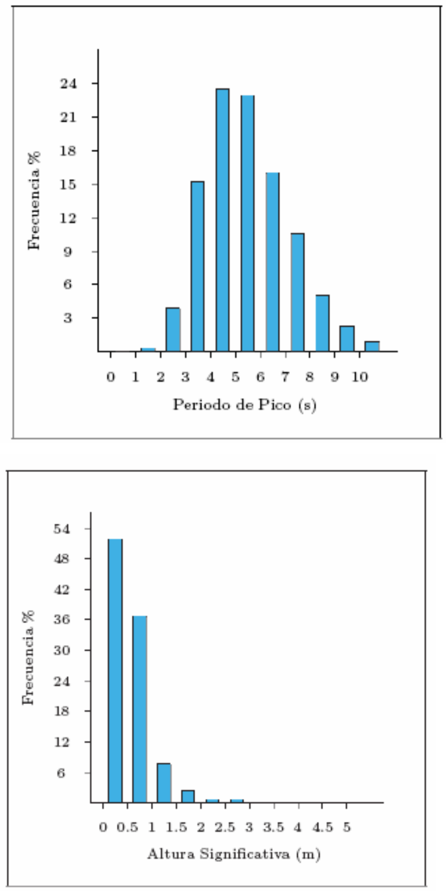

Figure 6: Joint distribution of Peak Period and Significative Height (September 1985 – December 2002)

6. Experimental tests and data analysis.

The experimental tests were carried out at the towing tank of the University of Trieste. The basin is 50 m long, 3.1 m wide and 1.6 m deep. The tank is equipped with two towing carriages (slow speed and high speed with motion measurement) and a wedge wave-maker that allows the generation of monochromatic waves.

The basin dimensions are relatively small and large models can not be tested in this facility. Moreover the choice of model dimensions is constrained by the characteristics of the waves to be generated, specifically relative length and frequencies of encounter.

The model scale used is 1:15.

The high speed towing carriage was used for seakeeping tests. A metal plate is fitted to the model and is connected to an arm containing the measurement equipment (see figure 7). The model is free to sink and trim and is not allowed to yaw by means of two slide guides at bow and at stern.

Speed, Heave, Pitch and total mean Resistance have been measured simultaneously.

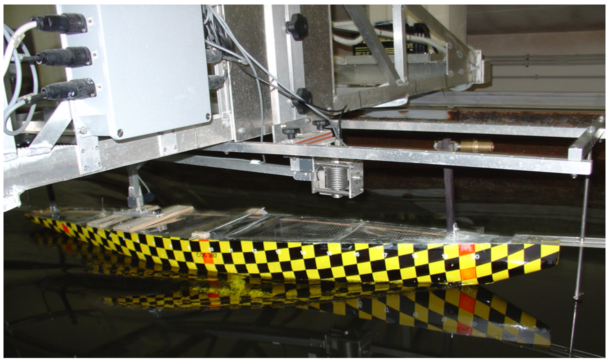

Figure 7: Acquisition instruments linked to the model

The position of center of gravity and longitudinal moment of inertia are those of the boat in sailing trim. We had no precise data about these two quantities, so we estimated them considering contributes of all the items in the boat, including crew and sails.

Seakeeping test of the model with the three optimized bulbs were carried out. The complete analysis of each configuration required 50 test runs, given by combination of 5 boat speeds and 10 wave frequencies. The experimental tests were carried out using 10 different wave periods with a step of 0.3 seconds. These periods were calculated from the corresponding peak period (in the 3.5-6.5 s range).

Five boat speeds were chosen and the encounter frequencies were calculated, considering a heading of 150 degrees, according to the following standard equation:

$$\omega_e = \omega - \frac{\omega^2 \cdot U}{g} \cdot \cos(150)$$

The encounter frequencies obtained were scaled (ω_{eM}) and wave frequencies to be generated in the towing tank were finally calculated to keep ω_{eM} constant, considering that the model has a heading of 180 degrees (bow waves) and the speed is scaled to keep the same Froude number.

A low pass filter has been applied to sampled records and a moving window Fourier analysis performed. Tests show that motion measurements are much more accurate than that of the resistance. Vertical motions are here measured by potentiometers whereas the resistance is derived by means of a load cell, the latter being typically characterized by large noise.

Mean value (a_0) and first harmonic amplitude (a_1, frequency equal to encounter frequency) are exported to an ASCII file.

These calculated values allowed us to compute the RAO (Response Amplitude Operator) of Heave and Pitch and the total mean Resistance in waves.

The Response Amplitude Operator of Heave is computed using the following formula:

$$RAO_{heave} = \frac{\varsigma_g}{a}$$

where ς_g is the amplitude of heave motion and a is the incident wave amplitude.

The RAO of pitch is computed as follows:

$$RAO_{pitch} = \frac{\vartheta_0}{\alpha}$$

where $\alpha = k \cdot a = \frac{2 \cdot \pi}{\lambda} \cdot a$ is the wave slope

and $k = \frac{2 \cdot \pi}{\lambda}$ is the wave number.

Selected results corresponding to full scale speed equal to 9.3 kn are shown in figure 8 to 10. Specifically Figure 8 and 9 show the RAO of heave and pitch respectively. Figure 10 shows the total mean resistance in waves in model scale. The calm water resistance is also reported for direct comparison.

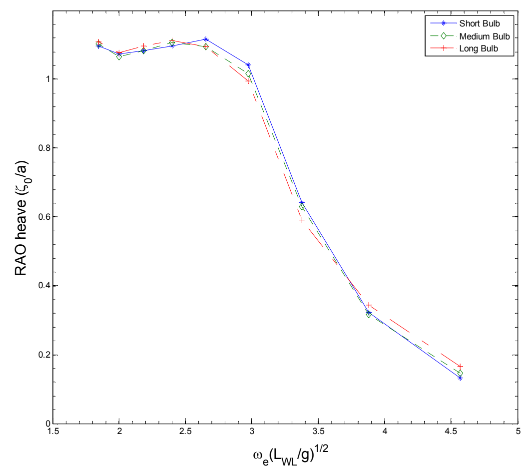

Figure 8: Response Amplitude Operator of Heave

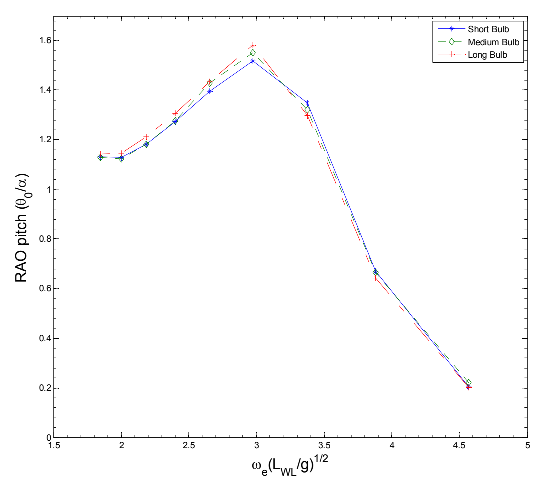

Figure 9: Response Amplitude Operator of Pitch

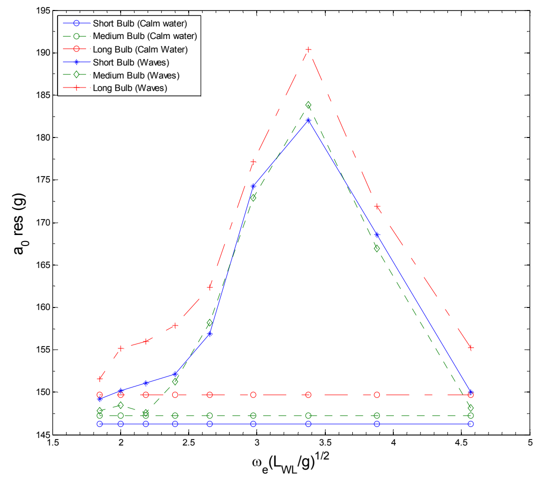

Figure 10: Total Mean Resistance in Waves (Model Scale)

7. RESULTS AND CONCLUSIONS

The aim of the work is a comparison between the performance in waves of a single hull shape fitted with different optimized bulbs. The results obtained allow us to derive some conclusions about the experiments:

As far as the vertical motions are concerned, heave (Figure 8) is very similar for the three bulb configurations while pitch presents rather large differences. Such a behavior can be explained considering that heave is influenced by the added mass coefficient which is lead mostly by the displacement and the waterplane figure. More remarkable differences have been noticed for pitch (Figure 9) because of the different longitudinal moment of inertia of the three different bulb shapes.

From this point of view the optimized short bulb performs better, with a maximum difference of 5% for the peak frequency, corresponding to the 4^{th} wavelength tested. The optimized long bulb performs better with high frequency waves (short waves): as a matter of fact the optimized long bulb increments longitudinal moment of inertia and added inertia of the boat, and so the pitch period. The model with the optimized long bulb has also a reduced relative pitch with long waves because it follows better the wave profile.

The total mean resistance (Figure 10) has a maximum for a specific frequency and it is interesting to notice that this frequency is different from that of maximum pitch. This probably happens because the relative motion between boat and wave is greater (the pitch motion is not in phase with the wave) generating an increment of the pressure component of the resistance.

We are confident affirming that the optimized long bulb presents the highest resistance value, both in calm water and in waves, because of its greater wetted surface, even if the maximum sectional area is lower than the other bulbs. The resistance of the medium and short bulb are quite close each other.

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