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Drag Reduction through Special Paints Coated on the Hull

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ABSTRACT: *The economic recession, the environmental impact as well as the continuous fossil fuel consumption encourage actions that focus on saving energy. In the vessels sector, one of the main objectives has always been to reach a hydro-dynamically optimum hull which gave the desired speed with minimum power.*

Hydrodynamic drag is basically divided into two parts: a) the friction between the water and the hull, and b) the wave generation due to the free-surface air-water. Presented in this paper, is the research which evaluates the possibility of friction-drag reduction by means of the coat of special paints on the hull.

The study has been applied to a fishing cooperation vessel on which hydrodynamic aspects had already been analyzed by the ETSI Navales Model Basin. Two plates with different paints have been tested with a wet surface equivalent to the model used in the previous hydrodynamic test.

Numerical simulations with a viscous code, which includes a roughness module, have also been carried out. The complete three dimensional system, including the free surface effect, has been considered. With these simulations it is expected to validate the roughness module of the commercial code.

1 INTRODUCTION

A series of hydrodynamic tests have been recently carried out at the ETSI Navales Model Basin at the Technical University of Madrid (UPM), to optimize a fishing cooperation vessel (FCV), (Pérez-Rojas et al, 2009). This vessel has been designed to carry out training activities in different countries through an advanced platform in which students can receive quality training with direct access to the most usual equipment in the fish extraction, transformation, preserving and marketing industry. A detailed description of the vessel can be seen in (Núñez-Basañez et al, 2008).

The scale model of the FCV was subjected to different tests such as resistance, open water propeller, self-propulsion, streamlines and seakeeping in regular waves. A complementary study with numerical tools enabled the estimation of the seakeeping in irregular waves with the description of the streamlines obtained in the previous experimental tests.

During the design process of the FCV, the maneuverability department decided to change the shape of the rudder to a more innovative design. A few specific hydrodynamic tests were conducted to study the new rudder and in order to obtain the wake behind, some numerical simulations were also made. These actions enabled the comparison between this new rudder and the original rudder.

Another important aspect of the FCV is the fouling control. Since the appearance of the first biocide-free anti-fouling paints in the early 90s, there has been a remarkable progress. Nowadays, anti-fouling paints have a base of silicone and fluorine polymers (fluoropolymer®) that noticeably improve their performance, in comparison with other silicone based paints. The FCV is coated with a special paint that is the most technologically advanced in respect to limiting the fouling growth. This paint creates a very smooth and slippery coat, with a low friction resistance, which prevents marine organisms from encrusting.

In order to compare the paint of the FCV to a conventional paint, two plates have been tested at the Model Basin. The aim of the tests has been to quantify the reduction of friction resistance due to the new paint. These experimental tests have been numerically reproduced to validate the roughness module of the software STAR-CCM+, (CD-ADAPCO). In this paper the validation study is presented.

2 EXPERIMENTAL TESTS

The FCV's model has been subjected to series of resistance tests. The model was built with the shape supplied by the client at a 1:25 scale. Two loading situations have been tested. The experimental results obtained at the model basin are presented in Figure 1.

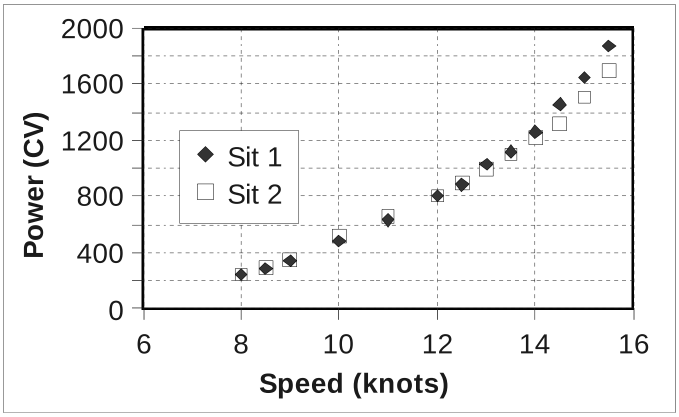

Figure 1. Model resistance at two loading conditions.

The multi-part object (MO) built to assess the effect of the painting on friction drag consists of a frame where two plates are mounted. The MO has almost no buoyancy, which is achieved by filling the hollow aluminum frame with foam. Figure 2 displays a sketch of the set-up. Paraboloid profiles have been attached both to the leading and trailing edges of the frame. In this respect, it should be mentioned that the MO utilized is similar to that used by the Naval Ship Research and Development Center (West, 1973).

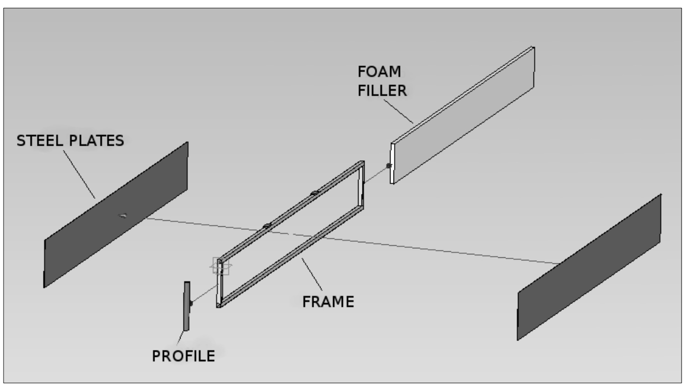

Figure 2. Sketch of the MO set-up.

Turbulence stimulators have been included, as they were in the model. These stimulators (pins) are small cylinders with a 3mm diameter, 2mm height, spaced 25mm apart and placed at 2cm from the leading edge of the plate.

The MO is immersed and attached to two small sliding carriages by means of two hydrodynamic profiles. Both carriages are inside a rail that is solidly connected to the towing carriage. This set-up prevents the MO from trimming and sinking. The MO is towed and the resistance is measured by a load cell, as performed in the model test case. A picture taken during a test can be seen in Figure 3.

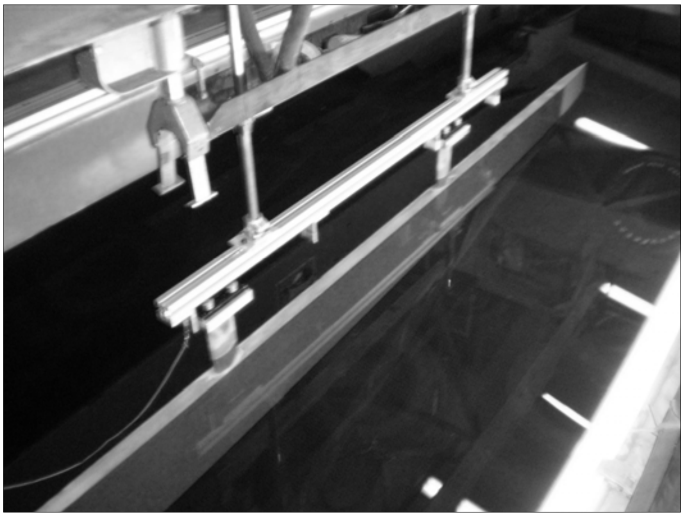

Figure 3. Picture of the system during a test.

In order to compare the conventional paint and the silicone based paint, two identical MOs have been built.

According to the client measurements, the conventional paint roughness height is about 120 µm and the silicone paint, 70 µm. It is expected that these MOs represent the Froude friction drag of an equivalent flat plate. The analyzed plates have the same wet surface and waterline length as the model at the loading situation 1, which was actually the design condition. This implies that plates are 3.088 meters long and 0.360 meters high. The client supplied the plates in order to guarantee that the tested plates would be painted using the same process as those used for the vessel.

Table 1. Mean measured resistance

Speed	Conventional	Silicone	Reduction
1.336 knots	1071 g	1037 g	-3.2 %
1.542 knots	1405 g	1382 g	-1.6 %

Six sessions have been conducted for each MO. Each session involves testing four speeds (7, 10, 13 and 15 knots) in one day, repeating each speed three times. That is, 12 trials for each session and 144 trials altogether. In this comparison study between the experimental and the numerical results, only the two highest speeds are considered. The 13 knots speed (Froude number, Fn = 0.22) becomes 1.336 m/s at model scale. Similarly, the 15 knots speed (Fn=0.26) becomes 1.542 m/s. In Table 1, the mean values of the measured resistances are presented.

According to the inter-centers calibration program, gathered in the proceedings of the 25th International Towing Tank conference (Resistance Committee Report 2008), the uncertainties of the ETSIN Model Basin are the values shown in Table 2. It is clear that these uncertainties are below the values of the drag reduction between the two paints.

Table 2. Model Basin's uncertainties

Fn	Uncertainties (%)
0.10	1
0.28	0.25
0.41	0.2

3 NUMERICAL SIMULATIONS

The numerical simulations have been carried out with the computational fluid dynamic software CD-Adapco's STAR-CCM+ 4.06.011, which is a Reynolds Averaged Navier Stokes Equations based solver. This software delivers the entire engineering simulation process in a single integrated environment. It is a user friendly software that includes the latest physical models and solver technology such as innovative meshing, model set-up iterative design studies, turbulence models, transition models, cavitation, six degree of freedom motion, among others. STAR-CCM+ is better geared towards complex geometries and complex physics (Azcueta & Rousselon (2009) in comparison with other similar software.

The calculations of this study have been run at a 8 Quad-Core cluster with a Linux 2.6.27-19-5 kernel (amd64). There have been simulated the two MOs used for the experimental tests: one, with the silicone based paint and the other, with the conventional paint. The discretized geometry encompassed the plates, the frame, the hydrodynamic profiles and both the trailing and leading edge bodies. The geometry and the physics are symmetrical. Therefore, the half of the geometry has been simulated. For a five millions elements mesh, the typical CPU time to achieve the desired convergence is around 24 hours using 8 processors of the cluster.

3.1 *Domain and mesh*

The MOs sail in two fluids: water (density = 997.5 kg/m^3 and dynamic viscosity: $8.871 \cdot 10^{-4}$ kg/m/s) and air (density = 1.19 kg/m^3 and dynamic viscosity = $1.855 \cdot 10^{-5}$ kg/m/s). The size of the control volume that contains these two fluids is established to reproduce the experimental tests conditions in the Model Basin. This is the reason why the domain is stretched from -8.4m to 20.35m along the X-axis, from 0m to 2m along the Y-axis and from -2m to 2m along the Z-axis (conventional coordinate system). The mesh is surface remesher and trimmer type with prism layers to properly capture the phenomena involved near the plates.

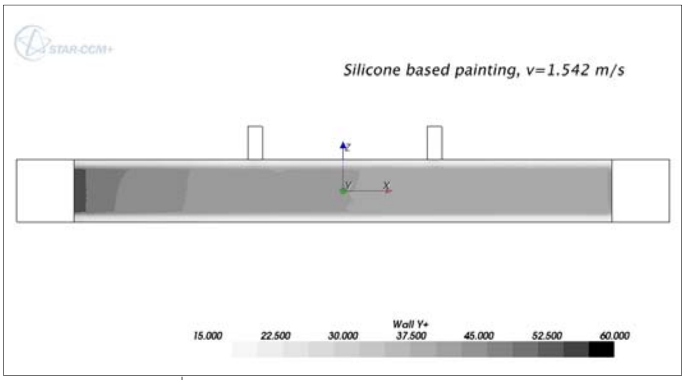

Figure 4. Wall y^+ over the plate

The first simulations have been conducted to study the convergence of the result with the increasing number of mesh elements and the quality. The variable to check the location of the first node of the mesh away from a wall is called "Wall y^+". It is the dimensionless distance from the wall and it is based on the distance from the wall to the first node and the wall shear stress. This value permits evaluating the quality of the mesh next to walls and it is related to the wall treatment chosen. It has been tried to achieve a Wall y^+ ranged between 30-50 over most of the plate as it is recommended (CD-Adapco), see Figure 4. The number of hexahedrons of the finally analyzed mesh is 5159084.

3.2 *Boundary conditions*

It has been tried to impose the most suitable boundary conditions, necessaries to reproduce the real behavior of the MOs:

- Inlet. The speed normal to the velocity-inlet surface has been set constant and different in each case (1.336m/s and 1.542m/s). The turbulence intensity has been set at 1% (low) and the viscosity ratio 10.
- Outlet. The hydrostatic pressure has been established in this boundary condition.
- Ceiling, ground, side-wall. These are smooth slip walls.
- Leading and trailing edge bodies, the frame and the hydrodynamic profiles. These are also smooth walls but no-slip condition is applied here.
- Dividing plane. It is considered a symmetry plane.

– Plate. This is a rough no-slip wall. This “rough” condition modifies the wall treatment to incorporate roughness by a reduction of the turbulent wall function coefficient. This reproduces the effect of the erosion of the inner layer by moving the logarithmic region of the wall law downward. As mentioned before, the conventional paint roughness height is 120 µm and the silicone paint, 70 µm.

3.3 *Numerical scheme*

The physical models used in these simulations are: VOF model, multiphase mixture, 6-DOF solver, segregated flow model, implicit unsteady approach, SST K-Omega turbulence model and all wall y^+ treatment. The most relevant characteristics of these models are detailed below.

The VOF Multi-Phase Model is used as interface capturing approach. This is a simple multi-phase model that is convenient to simulate flows of two immiscible fluids, capable of resolving the interface between the phases. In these cases there is no need for additional modeling of phase interaction, and the model assumption that all phases share the same velocity, pressure and temperature fields becomes a discretization error.

The 6-DOF Solver has been used to compute fluid forces and moments and gravitational forces on the MOs. In these simulations, the movements have not been allowed in order to exactly reproduce the experimental conditions, although this solver permits computing the translational motion of the center of mass of the devices as well as the angular motion of the body orientation.

The Segregated Flow Model is suitable for constant density flows as it is supposed they are in these simulations. This model solves the flow equations (one for each component of velocity, and one for pressure) in a segregated sequence. The linkage between the momentum and continuity equations is achieved with a predictor-corrector approach.

Due to the fact that the time scales of the phenomena of interest are of the same order as the convection and diffusion processes, the implicit unsteady approach is recommended. In the implicit unsteady approach each physical time-step involves some number of inner iterations to converge the solution for that given instant of time. The time step has set to 0.1s for all the simulations and the inner iterations to 5. The time step is around the 5% of the characteristic time which is the characteristic length (3.088m) divided by the speed (1.336m/s or 1.542m/s).

As usual, in order to close the RANS equations and determine the Reynold's stresses, a turbulence model is required. The model chosen is the SST K-Omega. This model was developed in 1994 by Menter. The SST accounts for the transport of the turbulent shear stress and gives highly accurate predictions of the onset and the amount of flow separation under adverse pressure gradients. The SST is one of the most popular turbulence models in external hydro/aerodynamics and it is used widely in the industry. The reason for the wide spread usage of this model is that it is robust; it allows an integration through the viscous sublayer without much computational effort and has advanced separation prediction capabilities, (Menter & Egorov 2007).

It is important to choose an appropriate wall treatment among this software's supplies, in order to capture the phenomena involved near the plates and resolve the viscous-affected region. In this case, the All Wall y^+ Treatment has been set. This options is the most general treatment that encompassed both the high-y^+ and the low-y^+. Furthermore, this treatment distinguish automatically between them.

4 COMPARISON OF RESULTS

In this section, the comparison between the experimental values and numerical results is presented. Table 3 displays the differences between the numerical results and the experimental values for the silicone based paint at the two speeds. As it can be observed, the differences are less than 1.5%, which are promising.

Table 3. Silicone paint

Speed	Experiments	Numerical	Differences
1.336 m/s	1037 g	1039 g	-0.2 %
1.542 m/s	1382 g	1363 g	1.4 %

In Table 4 the comparison for the conventional paint is presented. In this case, the results are even better because the differences between the experimental values and the numerical results are less than 1%. Therefore, the software is able to capture the increasing drag, not only with the increasing speed but with roughness too. The differences are smaller for the conventional case than for the silicone paint, which can indicate that the roughness module of the software is more appropriate for a standard roughness than for silicone based paints, where some special behavior may be expected.

Table 4. Conventional paint

Speed	Experiments	Numerical	Differences
1.336 m/s	1071 g	1062 g	0.8 %
1.542 m/s	1405 g	1403 g	0.2 %

The experimental values show a drag reduction of 3.2% for the low speed and 1.6% for the high speed. This is, the silicone based paint is actually better than the conventional paint regarding to friction drag. This fact is also reproduced numerically as it can be seen in Table 5.

Table 5. Numerical and experimental values of reduction

Speed	Conventional	Silicone	Reduction	
			Num.	Exp.
1.336 m/s	1062 g	1039 g	-2.2 %	-3.2%
1.542m/s	1403 g	1363 g	-2.8 %	-1.6%

The result of the reduction at 1.336m/s is -2.2% against -3.2% obtained with the experiments. The difference of 1% is mainly due to the numerical approximation (~0.8%). On the other hand, for the high speed, it has been experimentally obtained a reduction of -1.6%, whereas the result of the simulation is -2.8%. In this case, the 1.2% of difference is also the same order as the numerical approximation (~1.4%).

The point is that the experimental drag reduction between paints is of the same order as the numerical accuracy of the computational tool. In spite of this, the comparison between the numerical results of the drag reduction and the experimental values is reasonably adequate as the software is capable of predicting the effect of the roughness.

5 CONCLUSIONS

In order to compare the silicone based paint of the FCV to a conventional paint, two plates have been tested at the Model Basin. The reduction of friction resistance due to the new paint has been quantified. With these experimental tests the roughness module of the software STAR-CCM+ has been validated.

It has been assessed that nowadays, numerical tools are useful to efficiently compare solutions, not only qualitatively but quantitative too. It is concluded that there is good agreement between numerical calculations and experimental tests; even though, the experimental drag reduction between paints is the same order as the numerical accuracy of the computational tool.

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