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Dihedral bows: a new type of bulbous bow for small vessels

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Absract. This paper presents the experimental results of a new type of developable added bulbous bows that have been named as dihedral bows. These type of bows are based on polyhedral bows that are used in small vessels whose origin is traced to 1990's. The bow is designed with two developable surfaces that are designed following previous methodology on surfaces that consider material properties and will contain some chine lines.

Two dihedral bow designs and their towing tank tests are presented in this work in still water, comparing the effect of the dihedral bow vs. original designs. The tests covered displacement, semi-displacement and planning hulls, tested in two different loading conditions each and for different Froude numbers. The lines of the models are real ships.

An important reduction of the effective power (PE) of the ships with the dihedral bow was obtained from the experiments (About a 20%), and this successful cutback into the power is the main reason of this paper. Dihedral bows are a good option for efficient small ship design like the fishing vessels presented in this paper, and is open for larger ships.

Keywords: Ship Design, Bulbous Bow, Developable Surfaces

1 Introduction

A polyhedral bulbous bow is a type of bulbous bow very similar to the beak bows found on some large ships, but the main difference is that the polyhedral bow pierces the surface of the water rather than being fully submerged. This is the reason why these bows are sometimes mistakenly called wave-piercing bows. A polyhedral bulbous bow has marked chine lines in its definition, making it easier to produce and allowing it to be retrofitted to designs without bulbous bows, so it can be considered an added bulbous bow. These chine lines also mark the hydrodynamic properties of the bow.

The shape of a polyhedral bow is quite distinctive and can be well integrated into the original design or as an addition to the hull. A good example is shown in figure. 1. The ship on the top left is constructed in metal and the bulbous bow appears to be an addition. The one on the top right is constructed in GRP (Glass Reinforced Plastic) and the bulbous bow is integrated into the mould during construction. The chine lines can be well marked in the design, as in the previous ships, or softened when the bulbous bow is integrated into the design and the ship is produced by mould construction, as in the ship at the bottom of the figure. 1

The origins of this type of bow can be traced back to the 1990s, when some rescue and pilot boats in France were designed as double chine hulls with a forward polyhedral bow. These vessels combine a number of advantages; a finer entry in the forward sections, efficient spray rails to keep the deck dry and dampen movement in heavy seas, a more seaward shape in the forward slamming area, with a chine shape at the aft end to provide stability in following seas. These distinctive hulls are also known as Pantocarene hulls, after the French designers who began using them in the 1990s.

Figure 1 Polyedral Bows

A polyhedral bulbous bow, unlike a conventional bulbous bow, is not completely submerged. A conventional bulbous bow generates interference waves that reduce the wave resistance, while a polyhedral bow increases the buoyancy and its fine entry with a semi-angle of about 20º cuts the water surface, reducing the intensity of the diffracted waves, compared to the same hull without a bulbous bow.

This paper presents the design of additional polyhedral developable bows, which will be called dihedral bows. The paper focuses on still water, as the application examples presented are small boats, not designed for open seas, which stay in port in case of bad weather, or navigate in lakes or sheltered waters. This paper presents two vessels proposed by the FAO (Food and Agriculture Organisation of the United Nations) quite similar to the ones contained in its small vessel database. [1].

Although seakeeping has not been considered in this study, Pantocarene ships have proven and excellent seakeeping: the bulbous bow volume dampens vertical motions and the shape of the bow when fully submerged increases pitch damping, thus reducing vertical acceleration.

Another advantage of the dihedral bow is that the dynamic trim angle is reduced compared to the ship without a bulbous bow, as the fine entry reduces the vertical pressures and this has a large effect as speed increases. This is the reason why these bows work well on both displacement and semi-displacement vessels, as will be seen from the results in section 4.

Of minor importance in terms of resistance, but with a high impact on comfort on board, the dihedral shape reduces spray by deflecting the water in the chine and throwing it away from the hull.

A good design of a dihedral bow, together with a well-balanced design of the hull and the position of the centre of gravity, can produce a very good boat compared to a boat without a bulbous bow.

An analysis of the current literature has shown no results regarding polyhedral bows. Regarding developable surfaces in ship design, please refer to the references in [2], as the present paper focuses on ship design. Regarding bulbous bow design, the most important published works started in the last century and are the experimental work of Kracht in 1978 [3] and the theoretical work of Yim in 1974 [4] and Yim in 1980 [5]. The bulbous bow design is associated with the reduction of fuel consumption as in [6] and in [7].

This paper shows significant power savings when using a dihedral bow, in some cases close to 20%. A standard bulbous bow is designed for a FAO fishing vessel in [8], achieving a reduction in effective power (PE) of about 14%. An optimised bulb can produce bow waves that positively interfere with the waves generated by a hull, resulting in a reduction in PE of about (12 ~15)% [9], and in large vessels with bulbous bows generally have (12 ~15)% fuel efficiency than similar vessels without them according to [10]. Higher PE reductions have been achieved with the use of a dihedral bow, as described in section 4.

Regarding the geometric design of the bulbous bow surface, there are only a few references that define the surface parametrically, and most of them use B-splines curves and surfaces, as in [11] and [12]. Considering the previous literature, the novelties of this paper are the new design of bulbous bows with developable surfaces defined by significant curves and the important effective power reduction achieved. Unlike the conventional bulbous bow, the dihedral bow is not fully submerged.

2 Defining a Developable Polyhedral Bulbous Bow: the Dihedral Bow

A dihedral bow is mainly defined by two new surfaces added to the hull definition. This is shown in Fig. 3 where the red surface is the top surface and the blue is the bottom one. The key for defining these surfaces is to consider some representative curves in their definition and then to define a developable surface that contains these curves. The complete methodology to define a developable hull surface containing two representative curves is described by the authors in [2].

Some examples of these representative curves are shown in Fig. 4 and Fig. 5. The lower surface is defined with a curve called Keel line (K-line) and with the Chine line (C-line), while the upper surface contains the C-line and the Top curve (T-line).

The curves are dotted when they are inside the original hull volume and solid when they are outside. Therefore, the key to designing a dihedral bulbous bow is to consider the shape of these characteristic curves rather than the surface itself. Faired curves mean that the developable surface that will contain them will be faired. These curves will also characterise the hydrodynamic behaviour of the design.

The K-line should be well integrated with the shape of the keel in the original hull, and its shape marks the increase in waterline length with the bulbous bow. If the original hull has a solid keel, the K-line should be designed to match the width of this keel.

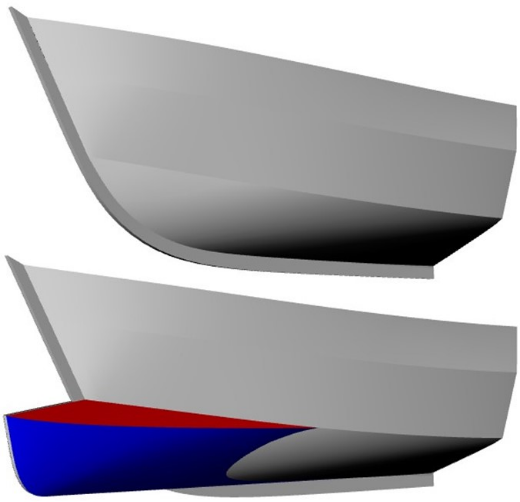

Figure 2 The 2 developable surfaces of a Dihedral Bow

The C-line marks the top of the underside, and the width of the C-line controls the angle of the waterline entry at the bulbous bow. If the original hull has chines in its definition, the C-line should be well integrated with their shape. This does not mean that the C-line of the bulbous hull must be tangent to that of the original hull, as this is not always possible. In the example of Fig. 3 right the chine continuity is maintained, which is also the case with the Pantocarene hulls. However, a good dihedral hull can also be designed without this continuity, as in the example in Fig. 3 left.

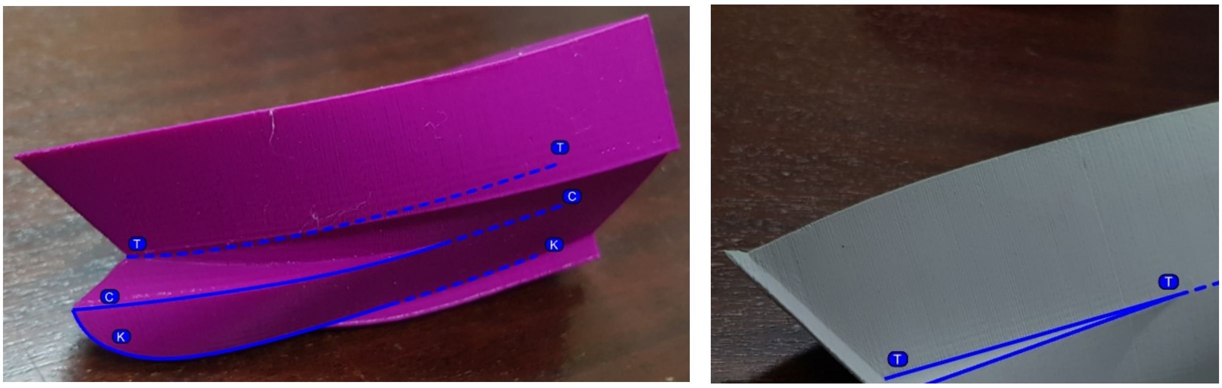

Figure 3 Example of curves: T-line inside the hull (left) and T-line over the hull (right)

The T-line defines the top of the surface and starts at the centreline of the ship, including the keel. There are two ways to define this curve: it can be included in the hull as shown in Fig. 3 Left, which is the best way to connect the chine of the dihedral bow to that of the hull, or it can be defined inside the hull, which gives more freedom in the design of the top surface, as in Fig. 3 right.

The two surfaces will produce intersection curves with the original hull. The upper surface produces a sharp and well defined curve that does not touch the water surface. The lower surface will intersect the hull in another curve, which can be very smooth as in Fig. 3 Left, or slightly marked as in Fig. 3 Right. Since the intersection curves are a consequence of the dihedral bow definition, they can be used to test a good design, especially the lower intersection that will be submerged, and it must be a soft curve without bumps and hollows.

As described in [2], a developable surface containing two directrices $\mathbf{s}_1$ and $\mathbf{s}_2$ can be obtained by obtaining different ruling segments r contained in the surface. A straight segment is a ruling if the normal vectors at its ends $\mathbf{n}_1$ and $\mathbf{n}_2$ are parallel. The above-mentioned paper describes a numerical technique for obtaining these rulings, taking into account the material properties.

In the case of a polyhedral bulbous, the directrix curves would be $\mathbf{s}_1$ = K-line and $\mathbf{s}_2$ = C-line for the lower surface, and $\mathbf{s}_1$ = C-line and $\mathbf{s}_2$ = T-line for the upper surface. Considering this set of two surfaces, their rulings can be obtained in conjunction as shown in Fig. 4. These formulae also have a design purpose, since they indicate the bending segments to conform the surface in the real ship.

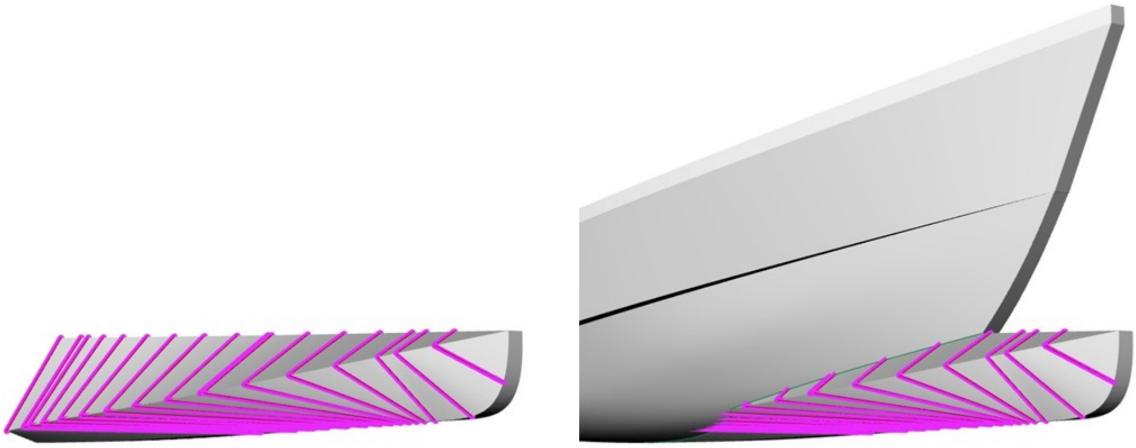

Figure 4 Ruling segments in a dihedral bow

In summary, once the directrices K-line, C-line and T-line have been designed, the rules can be defined numerically and two lofting surfaces containing these segments are obtained. The upper and lower surfaces are now designed and the intersection with the original hull can be calculated using CAD software to produce the final geometry.

3 Examples of two Dihedral Bows

Dihedral bows have been designed for two different vessels and their effectiveness in reducing power has been demonstrated based on towing tank tests of the original hulls without bulbous bows first and then considering a dihedral bow. These two ships have been supplied by FAO.

The addition of a bulbous dihedral bow allows a significant reduction in power and fuel consumption, resulting in more efficient and cheaper boats that can be of great social benefit in certain developing areas. This was the main motivation for this research.

Two loading conditions were studied, called Heavy and Light. The Light condition is used to navigate to the fishing ground, while the Heavy condition is used to return to port with the fish holds filled. The Light condition requires speed to get to the fishing ground early, while the Heavy condition requires speed to get to port first in order to keep the caught fish in good condition and to sell the fish at better prices at the fish market.

Tests were carried out with the same draught and zero trim between the vessels with and without the dihedral bow. The main shape parameters are shown in Tables 1 and 2 and computed as

Block coefficient : CB = Displacement / (LWL • BWL • T)

Area coefficient: CX = Midship Submerged Area / (LWL • BWL)

Prismatic coefficient: CP = CB / CX

Waterplane coefficient: CWP = Waterplane area / (LWL • BWL)

Table 1. Ship Data for FAO3

FAO 3	LOA (m) =	15.20	BOA (m) =	4.44

Heavy	T (m)	DESP (t)	LWL (m)	BWL (m)	Ax (m2)	AWP (m2)	CB	CX	CP	CWP
No Bulb	1.118	20.848	13.412	4.076	1.906	45.783	0.33	0.42	0.80	0.84
Bulb	1.118	22.516	15.023	4.076	1.906	48.254	0.32	0.42	0.77	0.79
Light							**CB**	**CX**	**CP**	**CWP**
No Bulb	0.914	11.555	13.189	4.024	1.097	42.78	0.23	0.30	0.78	0.81
Bulb	0.914	12.664	14.863	4.024	1.097	45.559	0.23	0.30	0.76	0.76

Table 2. Ship Data for FAO4

FAO 4	LOA (m) =	15.09	BOA (m) =	4.72

Heavy	T (m)	DESP (t)	LWL (m)	BWL (m)	Ax (m2)	AWP (m2)	CB	CX	CP	CWP
No Bulb	1.2	31.047	13.681	4.402	3.58	47.061	0.42	0.68	0.62	0.78
Bulb	1.2	33.231	14.647	4.402	3.58	48.153	0.42	0.68	0.62	0.75
Light							**CB**	**CX**	**CP**	**CWP**
No Bulb	1.082	25.624	13.59	4.144	3.07	42.275	0.41	0.68	0.60	0.75
Bulb	1.082	27.661	14.565	4.144	3.07	43.609	0.41	0.68	0.60	0.72

3.1 FAO3: semi-planning hull

The first example corresponds to a 15.2m GRP fishing boat and the original lines are shown in Figure 5. The hull is modelled in 3D and after testing the original hull, the dihedral bow was designed with the same drafts as tested in the original hull. A 3D view of both hulls and the two loading conditions is shown in Figure 6.

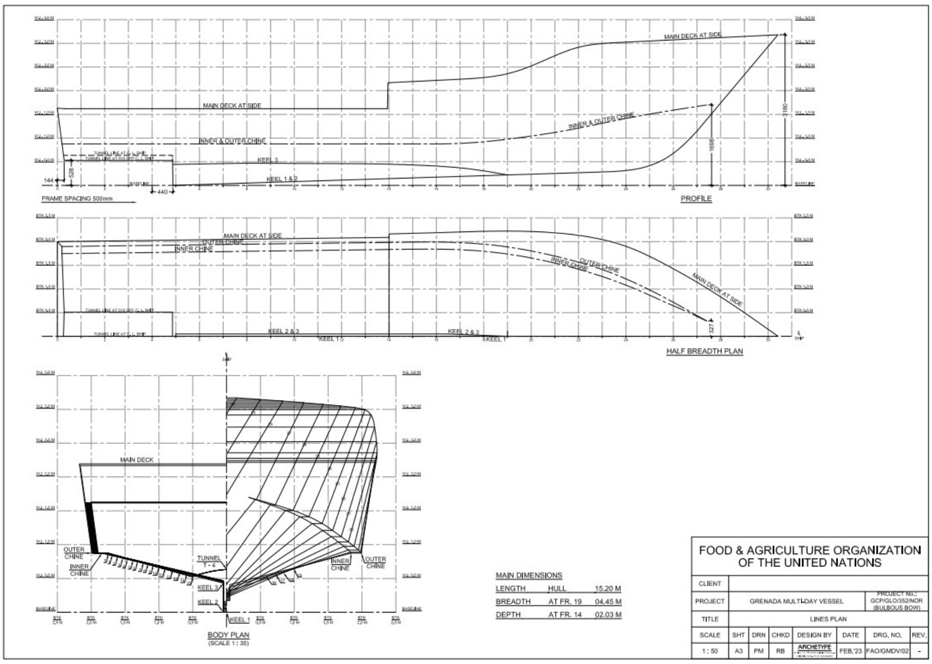

Figure 5 Original lines of FAO3

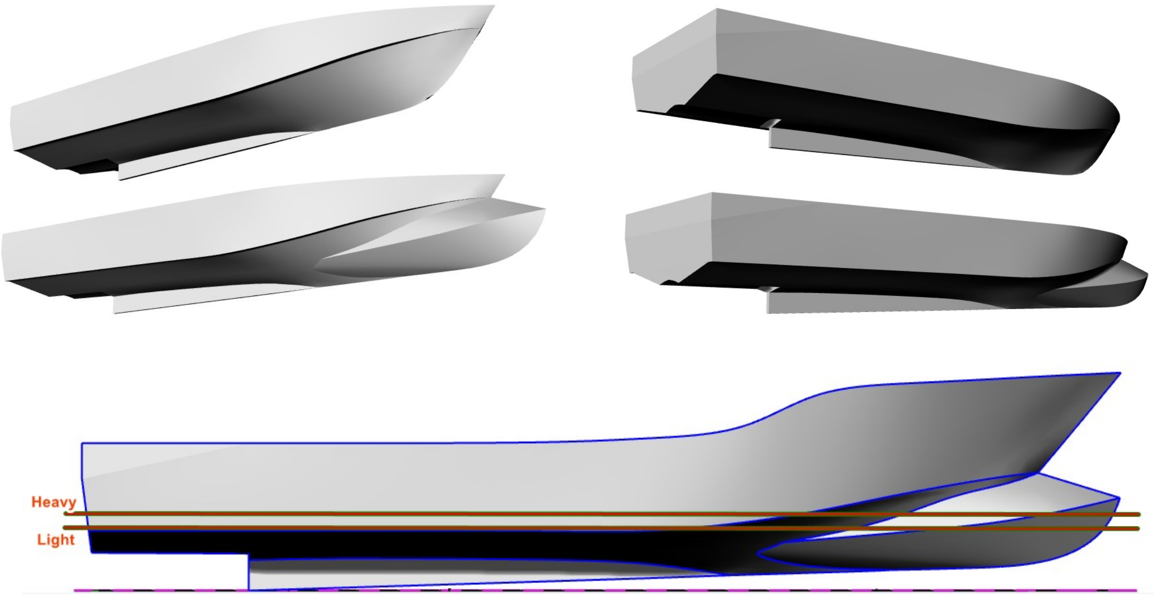

Figure 6 3D Views and Loading conditions of FAO3

3.2 FAO4: displacement hull

The second example corresponds to a 15.1m GRP fishing boat and the original lines are shown in Figure 7. The hull is modelled in 3D and after testing the original hull, the dihedral bow was designed with the same drafts as tested in the original hull. A 3D view of both hulls and the two loading conditions is shown in Figure 8. Note that both examples have chine lines in their definition, although in the case of FAO4 these curves are used for construction purposes, whereas in FAO3 the main purpose of such lines is hydrodynamic, looking for a planing attitude, especially in the aft part of the hull.

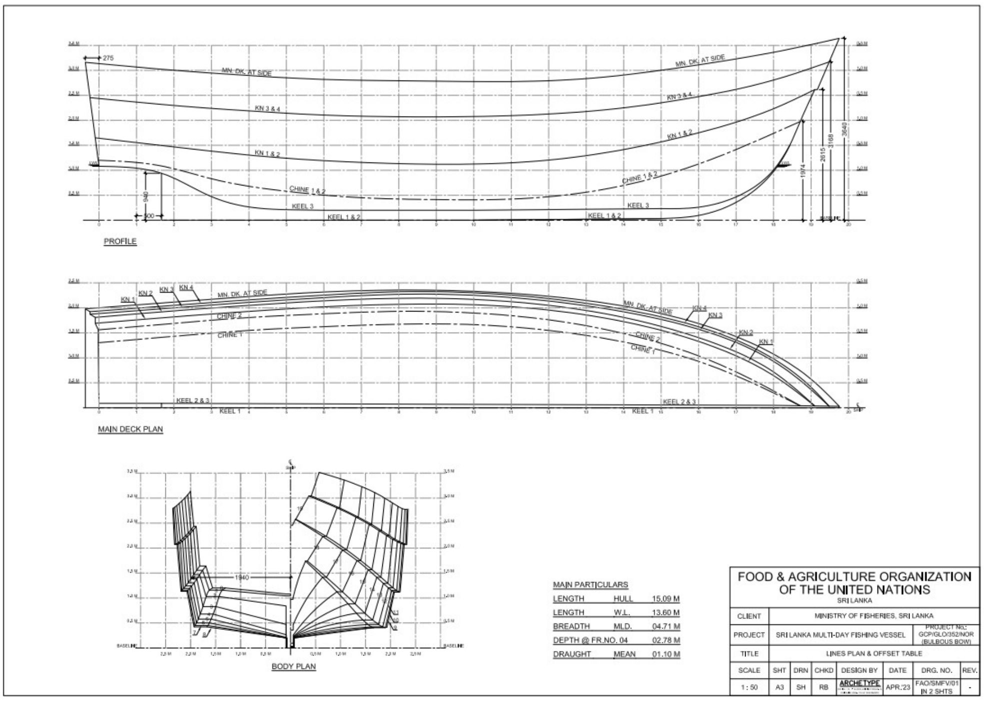

Figure 7 Original lines of FAO4

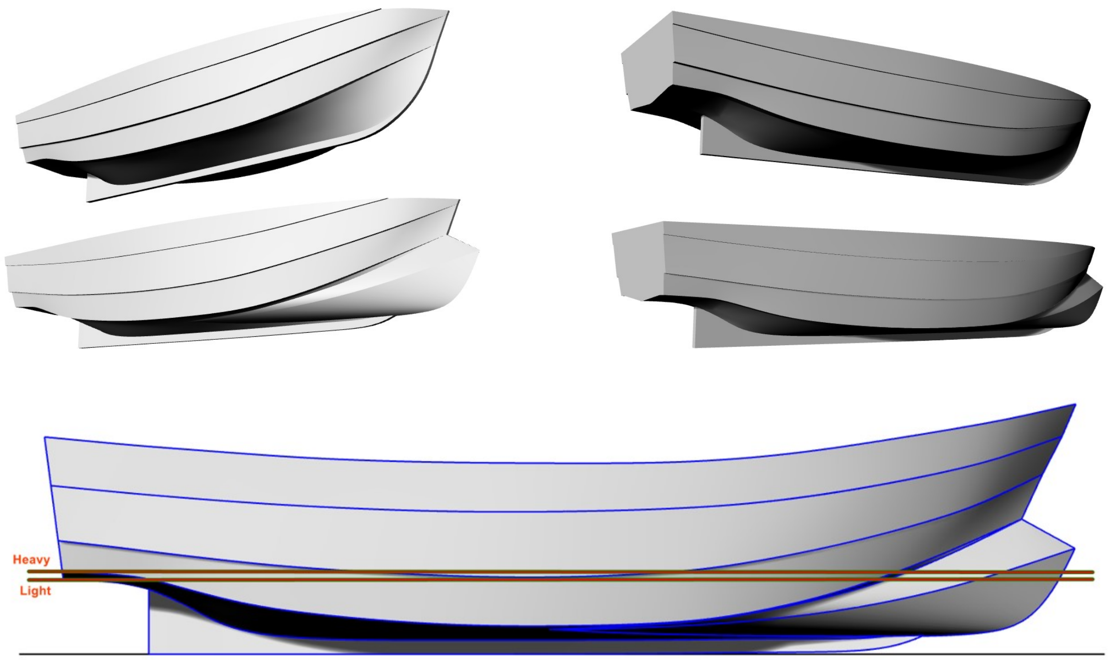

Figure 8 3D Views and Loading conditions of FAO4

4 Experimental power results in towing tank

The four designs presented in the previous section were tested in the model basin of the Naval Architecture and Marine Engineering School of Madrid (ETSIN) and were constructed to a scale of about 6. The towing tank was inaugurated in 1967 with dimensions of 56 m long, 3.8 m wide and 2.2 m deep, and was later enlarged to 100 m long. In Fig. 16 shows a cross-section of the tank. The tank is equipped with a trolley that can reach a maximum speed of 4.0 m/s.

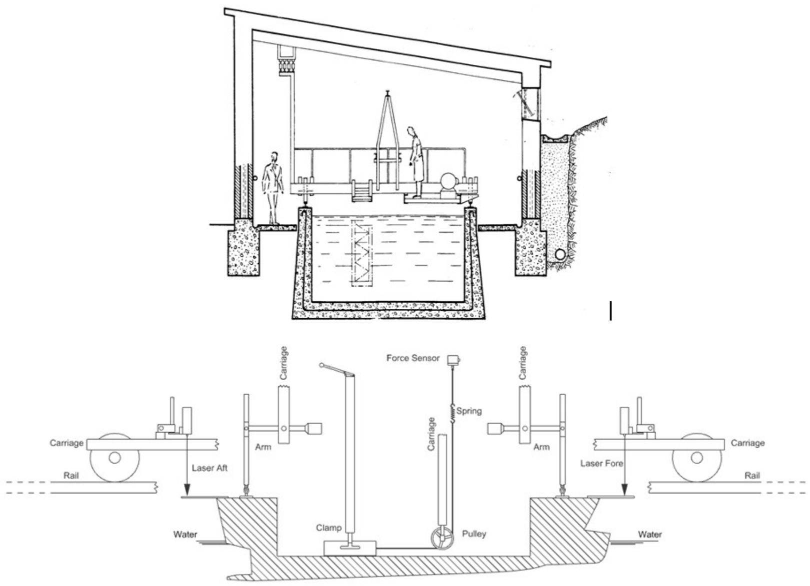

Figure 9 Transversal view of Tank at ETSIN and power test set up

Figure 9 shows a schematic of the test set-up. The model is connected to the trolley by two guide arms, a wire, a spring and a load sensor. Prior to each test, the zero point of each instrument was checked. Zero was also checked between runs. The minimum waiting time between consecutive runs was set at 20 minutes to obtain comparable conditions. The water level was also checked regularly to maintain a constant level throughout the tests. The water temperature was measured to extrapolate the results to full scale at 16ºC according to ITTC 2017 in [13]. Once the full scale resistance has been extrapolated using the ITTC method, the effective power (EHP) can be calculated by multiplying this resistance by the speed. The following figures show the EHP and also the dynamic trim angle for different speeds and Froude numbers.

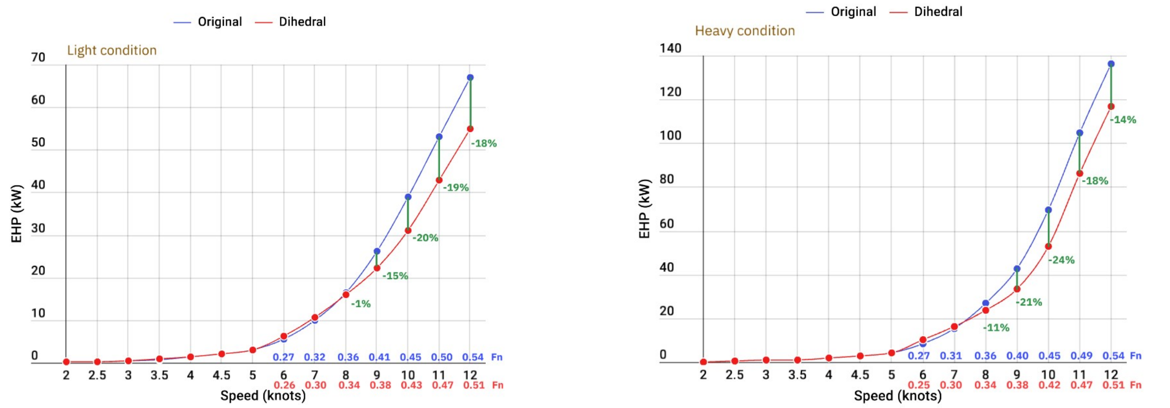

Figure 10 Power reduction in EHP for FAO3 in both conditions

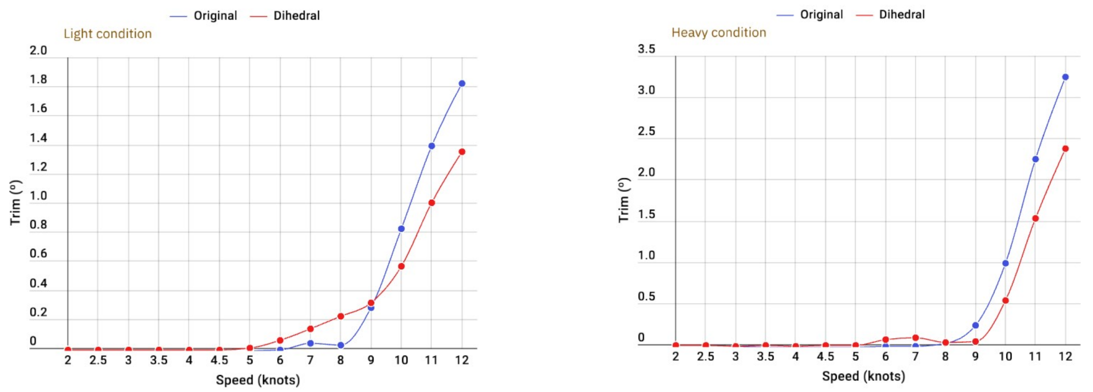

Figure 11 Dynamic trim angle for FAO3 in both conditions

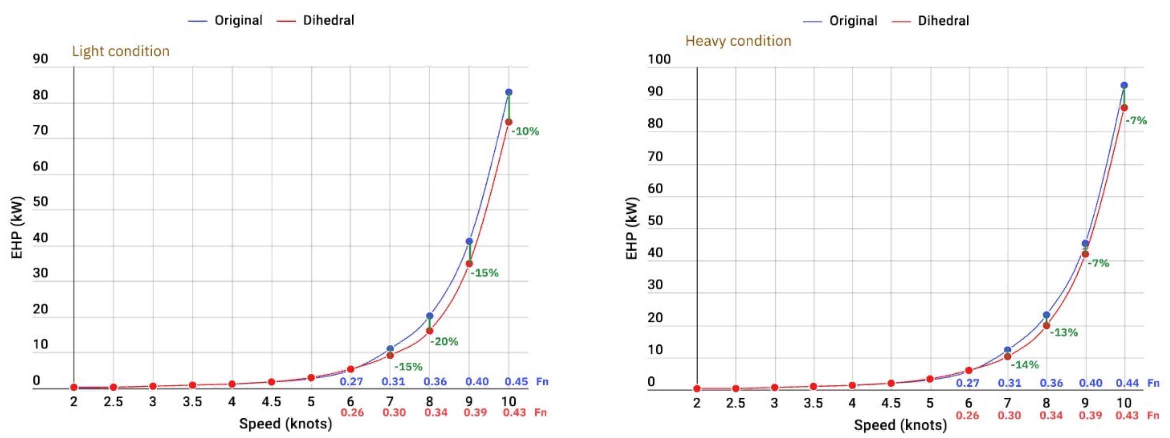

Figure 12 Power reduction in EHP for FAO4 in both conditions

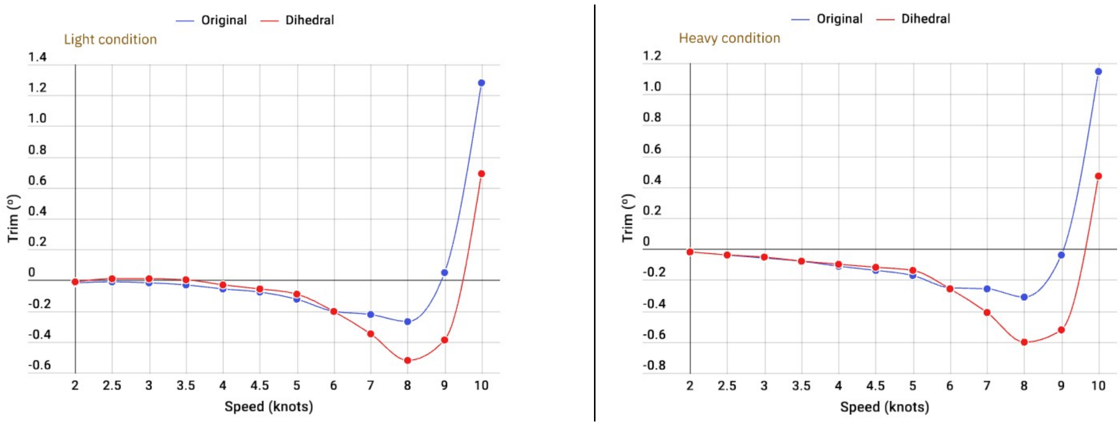

Figure 13 Dynamic trim angle for FAO4 in both conditions

5 Conclusion

The resistance tests show a significant reduction in the effective power of the two vessels FAO3 and FAO4 with the designed dihedral bow for both loading conditions tested. Effective power is the product of resistance and speed and is the power required to tow the vessel at the required speed, so the propeller effect is not taken into account.

The dihedral bow starts to work effectively at around 8 knots in both loading conditions for FAO3. At 11 knots (design speed) the power reduction is approximately 19% in both loading conditions. The maximum reduction in engine power is at a speed of 10 knots, with a reduction of 20% in the light condition and 24% in the heavy condition.

Trim angles are reduced in the boat with the dihedral bow, above 8 knots. This is also the speed at which the dihedral bow begins to reduce resistance. The resistance increases as the hull approaches design speed and the running angle increases as the boat tries to climb its own bow wave. So a low angle of heel has less resistance at low planning and semi-planning speeds and the dihedral bow has a positive effect by reducing the trim angle.

For FAO4, dihedral bow starts to work effectively at around 7 knots in both load conditions. At 8 knots (design speed), the reduction in power is approximately 20% in the light condition and 13% in the heavy condition. The maximum reduction in power is for the design speed of 8 knots.

Trim angles are reduced in the boat with the dihedral bow, above 7 knots. This is also the speed at which the dihedral bow starts to reduce resistance. The resistance increases as the hull approaches design speed and the running angle increases as the boat tries to climb its own bow wave. Therefore, at low planned and semi-planned speeds, a low running angle has less resistance and the dihedral bow has a positive effect by reducing the trim angle.

The tests were carried out for the same draught on both boats. This is conservative as the boat with the dihedral bow would have the extra volume of the bow and would be expected to float at a lower draft. However, the final weight will not be known until the modified vessel is built.

Acknowledgments

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