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SEMI-SUBMERSIBLE YACHT CONCEPT: RETHINKING BEHAVIOUR AT ANCHOR AND GENESIS OF THE COMFORT DRAFT

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SUMMARY

This paper presents an investigation done on motor yacht to improve the seakeeping characteristics at anchor by changing the hydrodynamic properties of the hull and not by adding stabilising devices (thus damping). The incentive of such approach came from design consideration with the presentation of semi-submersible concept for a yacht.
The change in loading condition combined with the change in waterplane area are the basis of the proposed concept. Both aspects contribute at modifying the hydrodynamic properties of the hull and minimising the wave excitations in order to, ultimately, reduce the motions. It defines a possible development of future hull forms and anchor operation, defining a new standard that could be called a comfort draft, both used to enhanced access to the water and to reduce the motions.

1. INTRODUCTION

Over the years, the motion at anchor has been a focal point in yacht design as it is considered a major cause of discomfort. Limitation of on-board activities affects people's enjoyment of yachts at anchor and can spoil their experiences at sea. The issue has been resolved with the development of smart and efficient active and passive stabilization systems. However, little attention is in general given to the hydrodynamic properties of the hull itself, while any improvement there could also contribute to the onboard comfort.
The present work offers to tackle the issue of motion with an innovative solution. It discusses essentially a new concept of a partially submerged-super yacht designed to not only transform super yachts into deluxe extraordinary submarines capable of partially submerging, but also reduce the effect of the motion at anchor by changing the loading from the initial draft to a so-called comfort draft.
From a hydrodynamic perspective: effort has been put on the design of the hull itself, the stability requirement and its changing hydrodynamic properties as function of draft. Aspects related to the immersion mechanism and structure are not covered in the present study.
From design perspective: effort has been put in rethinking interior and exterior design enhanced by a semi-submerged platform.

2. RETHINKING HOW TO TACKLE MOTION AT ANCHOR

A very important criterion concerning motor yachts is their behaviour at anchor. A motion such as roll becomes truly disturbing when laying at anchor outside harbour, as it can be rather large even with very limited wave height. This happens when waves come from beam and wave periods are tuned with the natural period of the vessel. Solutions found and applied for mega yachts are at the front edge in terms of research and existing developments of roll stabilising devices. MARIN had played there an important role in the past with the first model tests realised on the use of fins at anchor. This gave the start of nearly two decades of fantastic developments in adding damping in a mode shape which has little, with bilge keels, anti-roll tanks, zero speed fins of different size, shapes and movements, rotor with magnus effect or gyroscopes.

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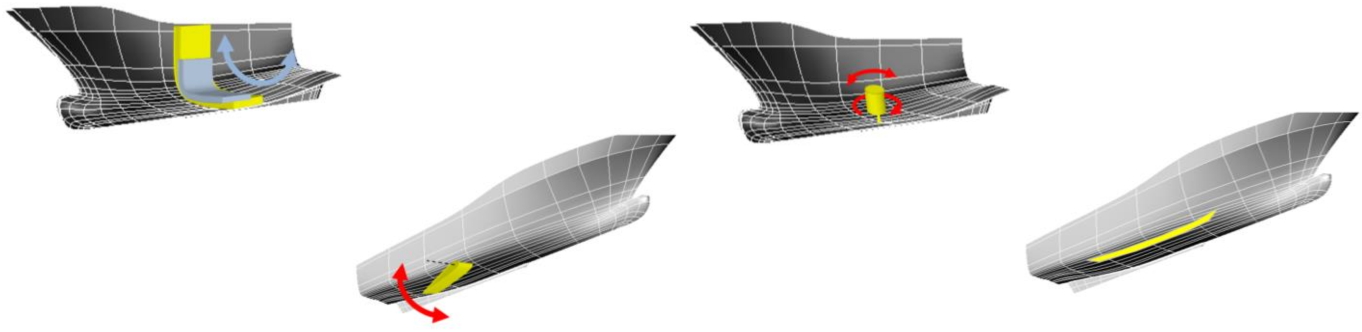

Figure 1: Different types of roll stabilising devices

However, roll is not the only motion reducing comfort at sea. The heave motion represents an issue as well, as it induces vertical accelerations which can cause fatigue and seasickness to the passengers and crew. This motion, however, cannot be damped and is usually accepted as an inherent limiting factor for comfortable operations and well being onboard. Wave as low as 1 m significant wave height are often the limit admitted by captain and crew.

In order to find a new breakthrough in increasing comfort, we had to think out of the box and look towards a new approach based on the design of the hull itself to minimise the wave excitation or to change the inertia properties.
As a first step, we did some calculations on an existing 55m yacht design to see the effect of varying the height of the centre of gravity. This was done without changing the draft, so without changes in the metacentric height.

Symbol	Magnitude	Unit
Lpp	55.21	m
B	11,6	m
T	3.4	m
GMt	0.7 / 0.99 / 1.3	m
KG	5.271	m
KM	6.451	m
Kxx	4.53	m
$T_{\text{natural roll period}}$	13.3 / 9.5 / 8.20	s

Table 1: Main particulars of the subject yacht

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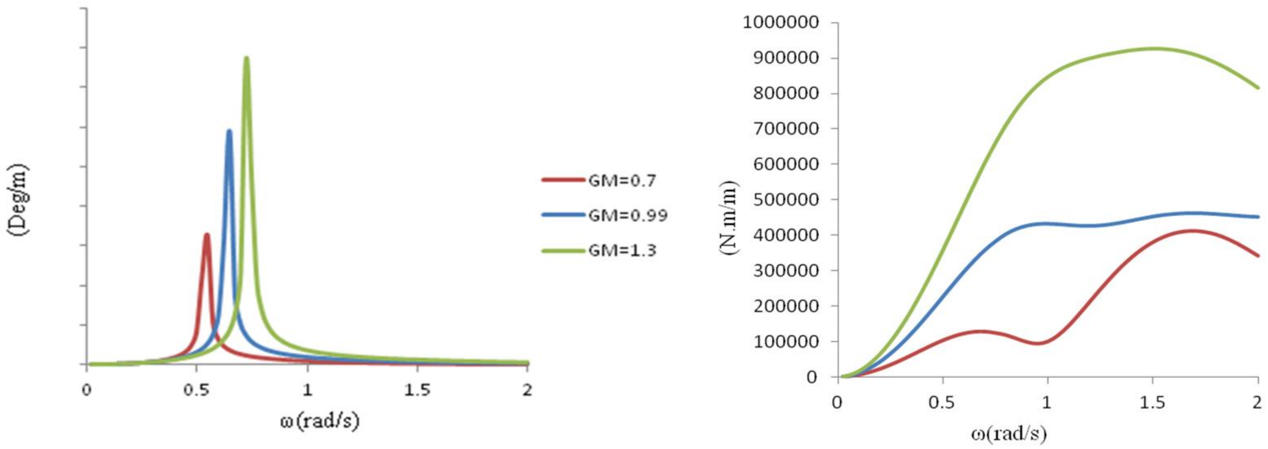

Figure 2: RAO of roll and roll excitation as function of wave frequency

As expected, the shift in GM towards lower values brings the natural roll period to longer magnitude, reducing the wave excitation and thus the roll response. This would be a principle to keep in mind in case ballast weights location can be chosen on a later stage with the semi-submersible concept.

3. NEMO CONCEPT: WHEN DESIGN MEETS HYDRODYNAMICS

The NEMO concept combines all the luxurious properties of a superyacht with an advanced technological design allowing the vessel to submerge partially below the water's surface like a submarine. The original concept was even more radical with the development of a fully submersed version (a submarine type yacht) developed by Edwin van der Mark and Harley O'Neill.
This design idea was spotted as a potential solution to also influence the hydrodynamic properties of the hull at anchor.
When benefits could be achieved to reduce the motions, this immersion of the hull could be characterized as a new feature: the comfort draft.

Figure 3: The NEMO concept at two different drafts

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4. CLOSE-BY PRINCIPLES AND CONCEPT

Figure 4: Semi-submersible and submersed heavy transport vessel

The pictures above show two types of ships capable of submerging while changing loading conditions.
The first one is a semi-submersible platform which is a specialised marine vessel used in a number of specific offshore roles such as offshore drilling rigs, safety vessels, oil production platforms, and heavy lift cranes. It shifts from an initial draft to a second called survival draft, in order to reduce the motion in storms.
The second one is a semi-submersible vessel with large decks designed to accommodate their colossal cargo. This type of vessel is also known as a "flo/flo", short for "float-on/float-off", and can carry loads weighing from 50 to 45,000 tons. In this case, the change in loading condition is not used to reduce the motions, but this example shows that with sufficient ballast capacity, it is possible to change draft drastically and keep stability requirements.

5. INTACT STABILITY REQUIREMENTS AND DEVELOPMENT OF THE FINAL HULL CONCEPT

The base design for the yacht was a 55m hull, which was lengthened to 105 m in order to allow enough ballast capacity to submerge the hull. Check on intact stability requirements were there needed, depending on where the ballast tanks would be placed, keeping in mind that the aim was to reduce the GMt while submerging the hull.

For a Passenger monohull yachts (accommodating 13-36 passengers), independent of length, operating in displacement mode shall meet the intact stability requirement below according to the IMO code of intact stability.

The requirements are as follow:

- The area under the righting lever curve (GZ curve) is to be not less than 0.055m.rad up to θ =30 angle of heel.
- The area under the righting lever curve is to be not less than 0.09m.rad up to θ =40° angle of heel or the angle of down flooding θf if this angle is less than 40°.
- The area under the righting lever curve between the angles of heel of 30° and 40° or between 30°and θf, if this angle is less than 40°, is to be not less than 0.03 m.rad.
- The righting lever GZ is to be at least 0.20 m at an angle of heel equal to or greater than 30°.
- The maximum righting arm is to occur at an angle of heel preferably exceeding 30° but not less than 25°.
- The initial metacentric height GM0 should be not less than 0.15 m.

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The figure below shows the initial hull design (slender monohull) and the table shows the main dimensions of NEMO's hull corresponding to the initial draught (4.2m) and the second draught (6.8 m).

Figure 5: slender half hull of the concept yacht

Symbol	Magnitude		Unit
Lpp	105	105	m
B	17,4	17,4	m
T	4,2	6,8	m
GMt	1,4	0,9	m
KM	8,01	7,795	m
KG	6,6	6,9	m
LCG	54,7	52,53	m
Cb	0,52	0,71	m
Cm	0,79	0,84	-
Cp	0,66	0,71	-

Table 2: Main particulars of the concept yacht

The GZ curves presented hereafter are obtained for the two loading conditions.

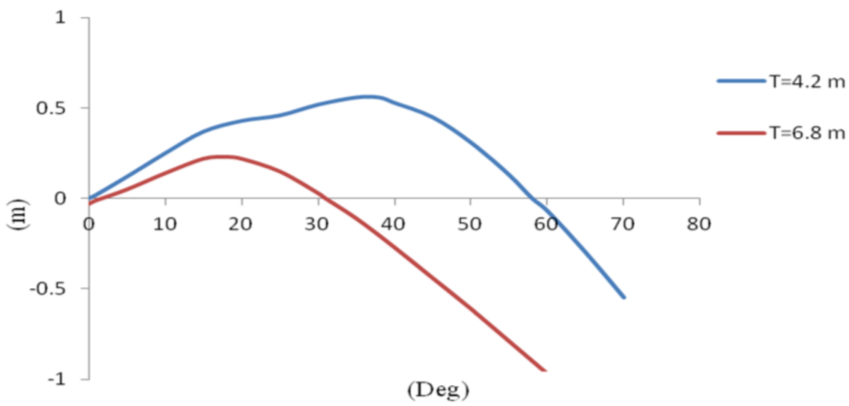

Figure 6: GZ curve

At first glance, we realize that the maximum righting arm corresponding to the second loading condition (T=6.8 m) does not exceed an angle of heel of 18°, which does not respect the intact stability requirements. Also other criteria are not met, even when changing the locations of the ballast tanks. No convergence could be found to accommodate both the intact stability criteria and the reducing in GMt which would reduce the roll response.

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We then identified that the decrease of the metacentric height GM, needed to reduce the roll motion, could happen in two ways in fact:

- Increase the vertical position of the center of gravity by loading weights higher, which would reduces the ship's stability reserve and consequently its stability in general.
- Change the shape of the hull by reducing the waterplane area to reduce the transversal inertia which would allow subsequently to reduce the vertical position of the metacentre.

The second aspect was the opening towards a solution and the continuation of the project.
In order to comply with intact stability requirements and with those related to the initial loading corresponding to a draught of 4.2m and to the final loading, corresponding to 6.8m, in which the vessel is submerged up to the main deck, and in order to reduce the transverse metacentric height, we have conceived different hull forms able to decrease the transversal inertia.

Figure 7: Transverse and longitudinal openings through the full width (tender garage and dock types)

Figure 8: Lateral and side opening (promenade deck and balcony types)

In studying those hull forms, many iterations and changed in longitudinal position of the openings were made. Each size and position means different ballast capacity. The solution presented in figure 9 was one of the best but creating such side opening in the bow area was not wished when sailing in waves. It was then decides to increase the depth of the side openings and concentrate them in the aft part of the hull.

In the selected hull form the waterplane area has decreased at the main deck in submerged condition (T=6.8m), and the capacity of the ballast needed to submerge the vessel is around 3387 m3. The space dedicated to habitability is 40% less compared to a yacht of the same size, which would make this 105m design comparable to a 55/65 m design.
The table below shows the main dimensions of the new NEMO's hull corresponding to the initial Departure draft (4.2m) and the comfort draft (6.8 m).

Symbol	Magnitude		Unit
Lpp	105	105	m
B	17,4	17,4	m
T	4,2	6,8	m
V	3526,8	6831,6	m3
GMt	1,4	0,9	m
KM	8,01	6,5	m
KG	6,6	5.6	m
LCG	54,7	54,7	m
Cb	0,52	0,57	m
Cm	0,79	0,77	-
Cp	0,66	0,74	-

Table 3: Main particulars of the final concept yacht

The GZ curves presented hereafter are obtained for the new concept in 2 loading conditions, which both fulfil the intact stability criteria.

General intact stability criteria	T=4,2	T=6,8
The area under the righting lever curve (GZ curve) is to be not less than 0.055 m rad up to θ=30° angle of heel	0,164	0,163
The area under the righting lever curve (GZ curve) is to be not less than 0.09 m rad up to θ =40° angle of heel or the angle of down flooding Of	0,259	0,241
The area under the righting lever curve between the angle of heel of 30 and 40 or between 30 and θf, is to be not less than 0.03 m rad	0,095	0,078
The righting lever GZ is to be at least 0.20 m at the angle of heel equal or greater than 30	0,52	0,5
The maximum righting arm is to occur at angle of heel preferably exceeding 30 but not less than 25	38	28
The initial metacentric height GM0 is not be less than 0.15 m	1,414	0,893

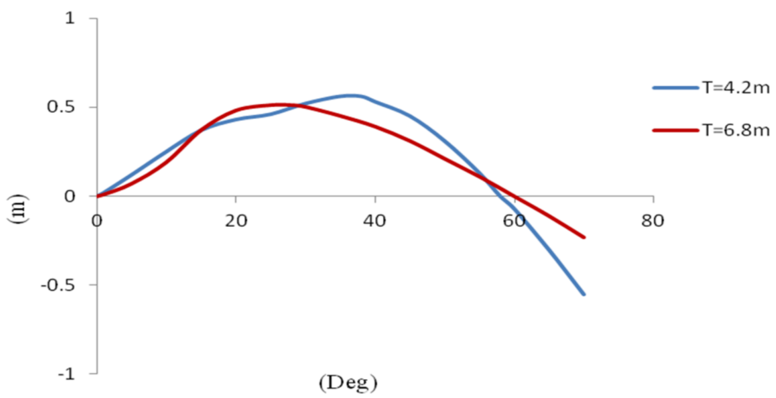

Figure 9: GZ curve and stability criteria

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The following figure summarises the basic principle of the semi-submersible yacht and its comfort draft.

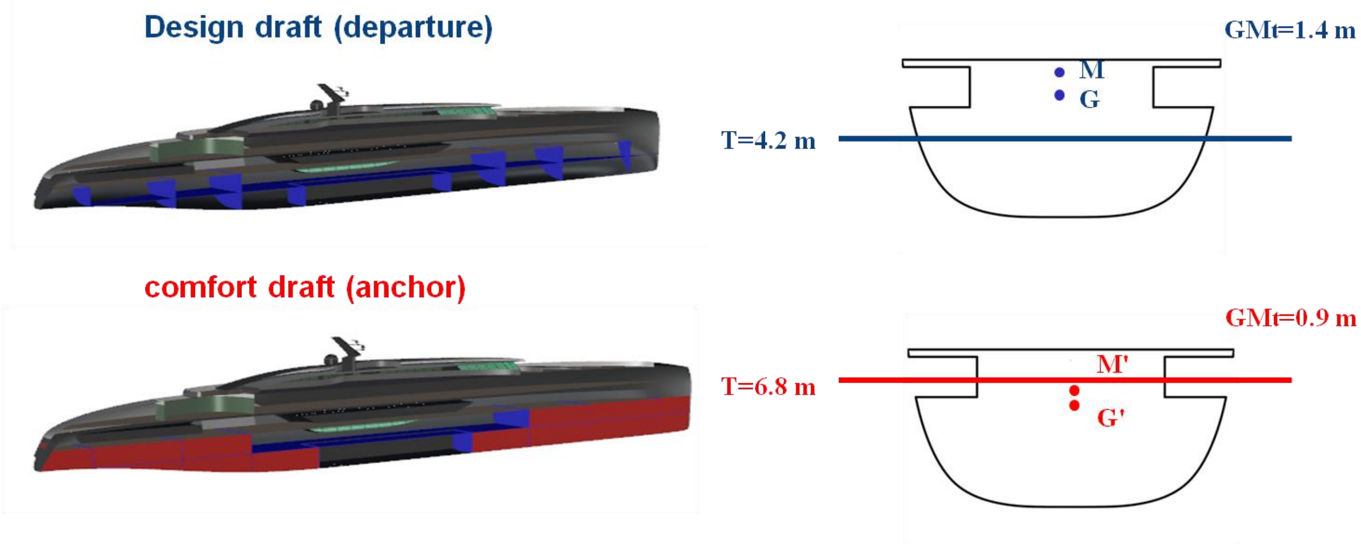

Figure 10: Principle of the comfort draft

Based on such concept, a new rendering of the yacht was made, in order to include as well aesthetic and design features.

Figure 11: Rendering of the developed hull form

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6. HYDRODYNAMIC PERFORMANCE OF THE COMFORT DRAFT

Seakeeping calculations were performed with a linear potential code, based on 3D diffraction method and in the frequency domain. Attention was paid on the panel generation around the opening, in order to avoid large horizontal panels located to close to the water surface, which could cause numerical issues. The results obtained are in line with the expectations and presented here after in the form of RAOs (Response Amplitude Operators), both for the motions and for the excitations.

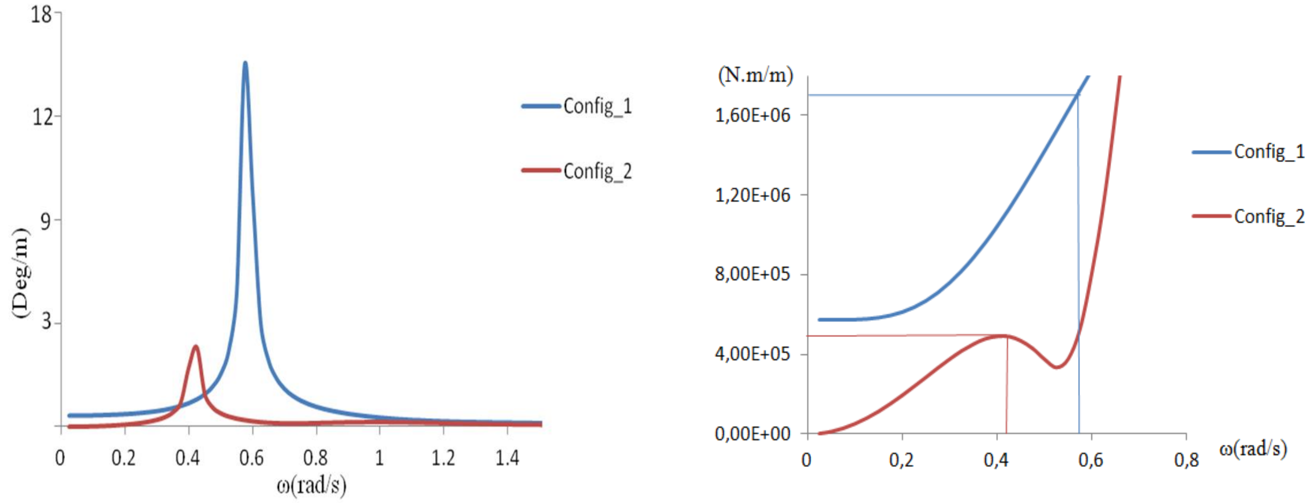

Figure 12: RAO of roll (left) and RAO of total roll excitation (right) obtained with the program DIFFRAC

The effect on the reduction of roll can be clearly seen in the figure left. This reduction is mainly due to the reduction of the roll excitation at lower frequency, as shown by the figure on the right. The figure below shows the reduction of standard deviation of roll and Effective Gravity Angle (EGA) in 1m significant wave height and different wave peak period, in beam seas.

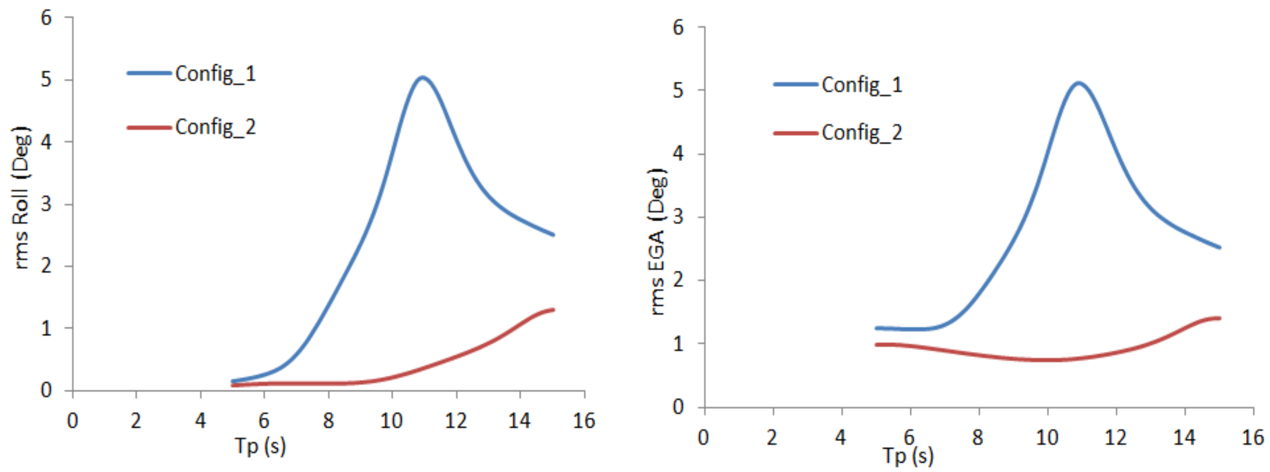

Figure 13: Standard deviation of Roll (left) and EGA (right) for different Tp and for Hs=1m in beam seas

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Even further optimisation could be achieved to investigate different ballast location for example or other openings geometry to further reduce the roll excitation. Of course, any change should also be checked back at intact stability requirement level.
However, the effect already obtained is drastic and equivalent or better than most of the active stabilisation devices. Only in longer wave (swell types) the effect is somewhat lower than capacity of active stabilising devices. In terms of operational performance, the following scatter diagram shows the limiting wave condition at which the vessel would operate without exceeding criteria on roll.

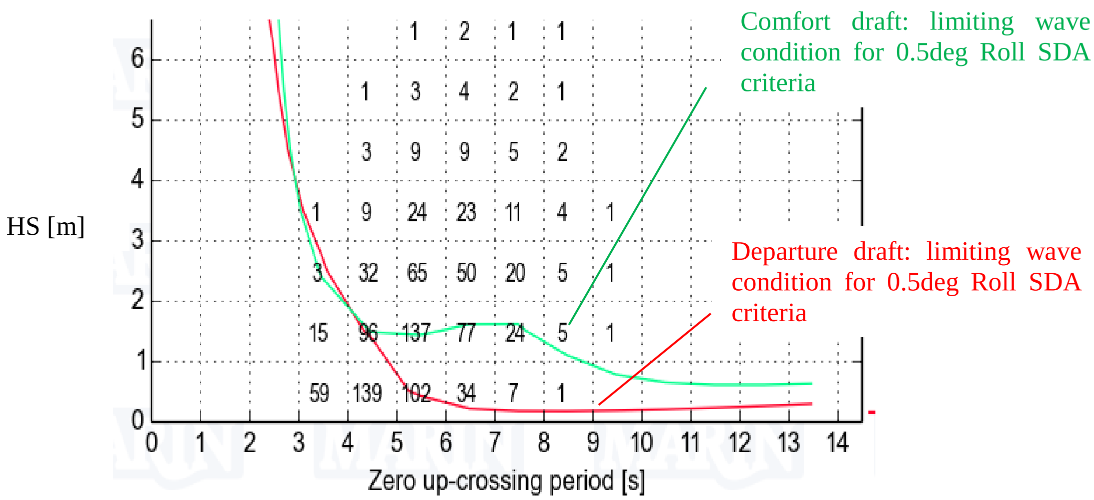

Figure 14: Scatter diagram of the Mediterranean Sea with maximum

A small waterplane area at submerged draft is also yielding drawback, due to a lower damping in the vertical plane and a shift in natural heave response. The following figure shows the response of heave.

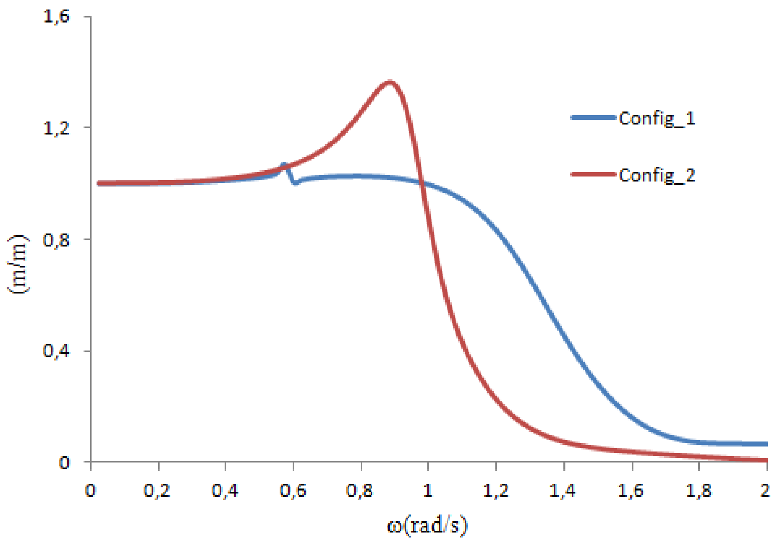

Figure 15: RAO of Heave in beam seas obtained with the program DIFFRAC

The increase in heave amplitude at certain wave frequencies is to be found back into standard deviations for waves longer than about 6 seconds in beam seas and shorter than 7 seconds in bow-quartering seas. The following figure presents the results in 1m significant wave height and various wave periods for two different headings.

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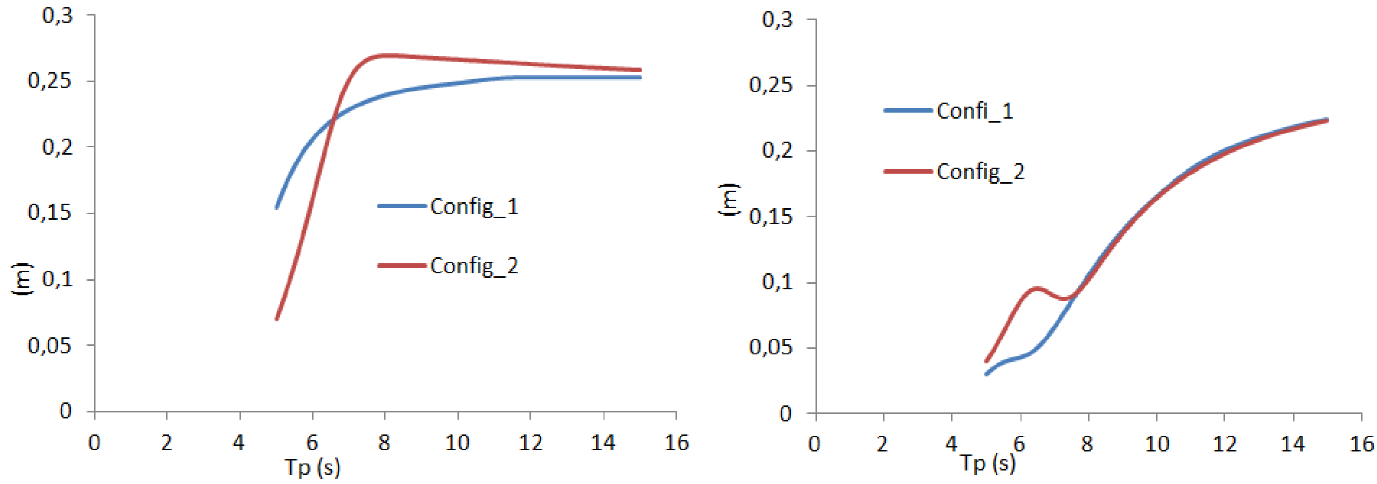

Figure 16: Standard deviation of Heave in beam seas (left) and bow-quartering seas (right) for different Tp and for Hs=1m

Maybe more interesting and important is the effect of the heave on the vertical accelerations, which are the main factor for risk of seasickness. On that point, the conclusion can be done, based on the results presented here below, that a drastic reduction of vertical acceleration in short waves can be achieved with the comfort draft. For waves longer than 8 seconds, no difference should be noted.

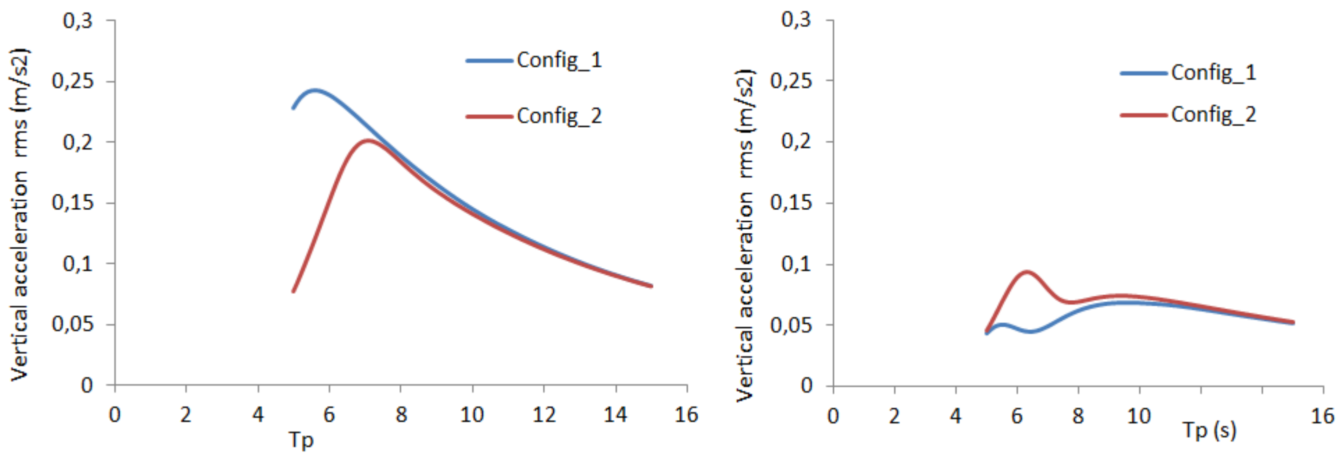

Figure 17: Standard deviation of vertical acceleration in beam seas (left) and bow-quartering seas (right) for different Tp and for Hs=1m

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7. CONCLUSIONS AND FURTHER WORK

The goal of the project was to develop a concept hull form which would benefit from a deeper draft at anchor, in order to improve her seakeeping characteristics.

The concept had to fulfil the stability requirements, which was obtained by combining ballasting and change of cross section, inducing a reduction of the waterplane area in submerged conditions.

The Comfort draft proves to be viable from a hydrodynamic and design point of view, as the roll motion is clearly reduced. Further investigation on the heave response must be conducted in order to make sure that the accelerations could also be reduced in a wide range of wave frequency. This could lead to different waterline area shape.

The principle of changing waterplane area could also be obtained with minimal draft change or by openings close to the waterline in departure condition.

Further work should obviously be addressed for the engineering of such solution (interior arrangements, damaged stability study, noise & vibration, ballasting systems and strength calculation), the possible side effect during ballasting operations (safety, free surface effects), and the acceptation of such concept for the yards and owners, as well as requirements from classification societies.