Previous sailing yachts seakeeping investigation in view of a new set of rules

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ABSTRACT

Sailing boat dismasting is an impressive and dangerous event which consequences are obviously critical. The causes that can lead to dismasting just start to be precisely investigated and understood. As a matter of fact, rules of classification societies are nowadays quite poor when it comes to mast and rigging. Indeed, these causes are intricate and of different kinds.

One of the reasons of dismasting is the lack of good estimations of the loads that will be applied to the mast and rigging. Part of these loads is due to ship motion in waves, mainly pitching.

This work is a study of the pitching behavior of sailing vessels at sea with *HydroStar* software. It is a potential flow solver using panel methods and developed by *Bureau Veritas*. Only linear theory is used here. The aim of this paper is to study what are the main parameters that drive a sailing boat pitching behavior. It is a first step in the view of building a simplified method to be able to quickly estimate inertial loads due to waves.

First, the global problem of seakeeping and the method used by *HydroStar* to solve it are briefly presented. Then, pitching motion results in regular waves are shown and analyzed for a small set of modern sailing yachts hulls. Despite the small size of the database a first simple method to estimate pitch response amplitude operator is proposed, based only on boat length.

Afterwards, method and results about acceleration in the mast are discussed. A very rough but quick formulation to evaluate the longitudinal acceleration or force in the mast is set.

A state-of-the-art process is then applied to enlarge results to irregular sea states and compute time series. Good agreement with some real full scale measurements is shown in term of pitching. The sea state parameters influence on pitch motion is studied and the concept of irregular RAO is proposed.

The influence of different ship parameters is then studied leading to a short list of key parameters.

To finish, a real case scenario is performed using all the previous conclusions on the yacht *Kiboko*. The aim of these results is to be further compared to on-board measurements that may occur in the next months.

1. INTRODUCTION

From a classification society point of view, yachts and particularly sailing yachts present really specific issues. Unlike for commercial vessels owners, money is not the main problem of sailing yachts owner. They take risks and put the ship in situations that a commercial boat would avoid. They always want to be faster.

Of course, such a philosophy sometimes leads to accidents. Dismasting is a critical one. Not only the ship loses its main propulsion system but also the fall of the mast may be dangerous for the crew or passengers. Rules concerning the mast scantling are today very poor. In *RINA* rules for sailing yachts [5], it is said:

"Each yacht is to be provided with masts, rigging and sails sufficient in number and in good condition. The scantlings of masts and rigging are left to the experience of builders and shipowners."

The main reason explaining this is the lack of understanding of the loads to which the mast will be submitted. Indeed, these loads are of two kinds. The most obvious is the aerodynamic force due to wind in the sail. Thanks to wind theory, these forces are quite well understood in steady state. Another kind of loads is due to ship motion in wave – mainly pitching. Indeed, pitch motion leads to strong inertial loads in the mast. In addition, it alters the steady aerodynamic forces in a non negligible way, as shown in recent works (e.g. [1],[4]).

Part of the work to understand more accurately the effective loads in the mast is thus to be able to estimate the ship motion at sea. From a classification society point of view, the aim would be to build a simplified process to be able to quickly estimate the ship pitching behavior and the induced acceleration in the mast. With such a process, new rules for masts and rigging scantling could be proposed. This work is a first step in that direction.

In this work, the software *HydroStar* is used to evaluate the ships response amplitude operators (RAO). It is a potential flow solver based on panel methods. It is developed by *Bureau Veritas*. All this work lies under linear theory.

In the two first parts, the general seakeeping problem and the method used by *HydroStar* to solve it are briefly exposed. In the third part, the small database of modern sailing boat hulls on which calculations have been performed is presented. In the fourth part, results in term of pitch RAOs are shown and discussed. A quick formulation based only on boat length is proposed to evaluate roughly a pitch RAO for a modern sailing boat. In the fifth part, a discussion is made about acceleration in the mast evaluation. In the sixth part, a state-of-the-art method to extend the results in irregular sea is presented and the effects of sea state parameters are analyzed. In parts 7 and 8, influence on pitch motion of some ship parameters is studied. Finally, in part 9, a real test case is performed using all the previous exposed methods and conclusions.

2. SEAKEEPING THEORY

2.1. General Problem and conventions

Seakeeping addresses the problem of ship motion at sea due to waves. The motion of the ship is decomposed into 6 basic motions (3 translations and 3 rotations) also called 6 degrees of freedom (DOF). This is depicted in figure 1 where the convention for the axis and rotations can also be seen.

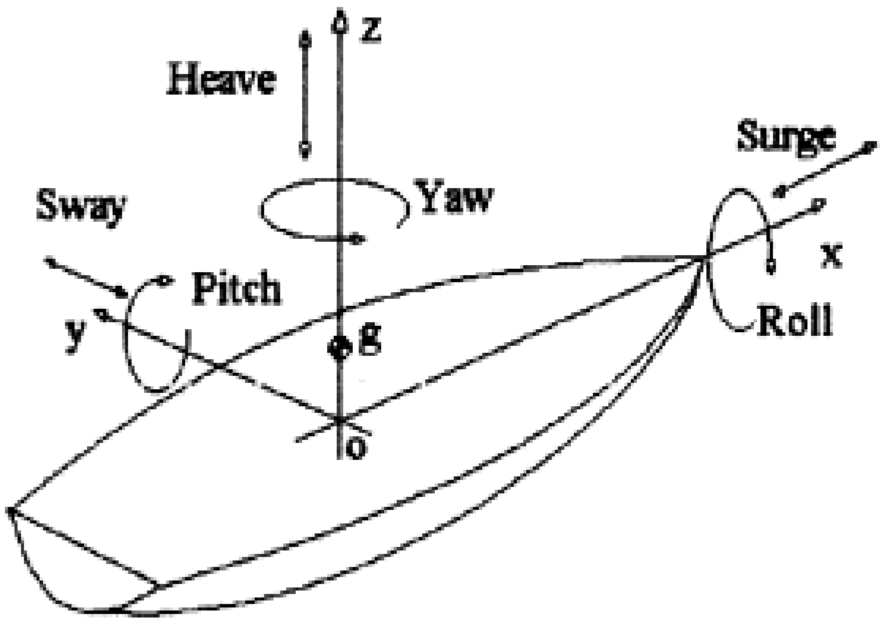

Figure 1. Ship 6 degrees of freedom and axis convention

The notations for these 6 DOF follow the usual convention:

x_1: surge

x_2: sway

x_3: heave

x_4: roll

x_5: pitch

x_6: yaw

The time derivative of any value *x(t)* is written $\dot{x}(t)$. In the following, pitch motion will be specifically studied.

2.2. Overview of Methods

To forecast seakeeping behavior of a vessel, different methods are available. First, experimental measurement can be carried out on a ship model in a towing tank. Experiments are ideally performed in a wave basin or, with fewer possibilities, in a regular basin.

Less expensive, numerical computations can also be carried out. Different solutions are possible, depending on the numerical model used. The first numerical solutions developed for seakeeping applications were using a *2D* potential model called strip theory. It solves the problem section by section. The most famous strip theory software is called *Pdstrip*. Now that computational power has largely increased, it has been abandoned.

Indeed, *3D* potential flow solver using panel methods are today the state-of-the-art concerning seakeeping. They need only few minutes to give seakeeping results as *RAO*s. They usually use linear theory and frequency domain approach, including more on more non-linearity. The most famous software are *HydroStar, Aquaplus, Seakeeper…*

Seakeeping results may also be obtained using more accurate solvers (e.g. RANS solver like *Star-CCM+*) at the cost of a bigger computation time (few hours or days). RANS solvers may be more used in the future when more powerful wave models will be available.

In this work, the potential flow solver *HydroStar* developed by *Bureau Veritas* is used for seakeeping computations.

2.3. Linear Theory

HydroStar uses what is called a frequency domain approach. The interest of this approach comes from linear theory which leads to first order results. Let us start from the beginning and consider a linear (also called regular or harmonic) wave in *1D*. The surface elevation can be written:

$$\eta(x,t) = A * \cos(\omega t + kx) \quad (1)$$

With:

- $\omega = 2\pi f = 2\pi/T$ the wave pulsation (rad/s). T is the wave period (s) and f the wave frequency (Hz).
- $k = 2\pi/\lambda$ the wave number (rad/m). The wavelength is noted λ.
- $A = H/2$ the wave amplitude (m). The wave height is called H.

An example of the plot of the free surface elevation at $x=0$ in function of time can be seen in figure 2.

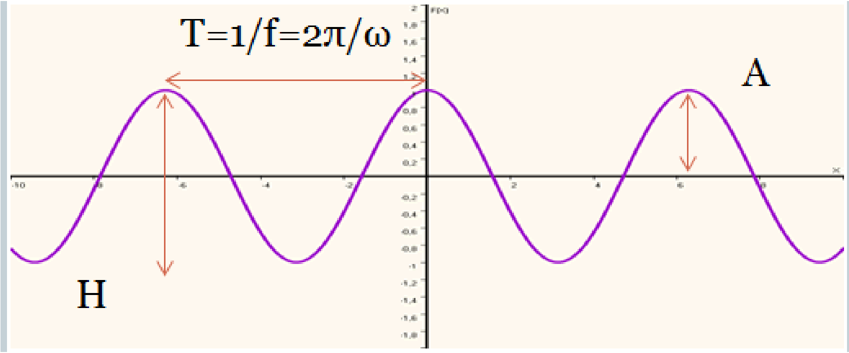

Figure 2. Free surface elevation at $x=0$ in function of time

Linear wave theory in infinite water depth gives an important relation that will be largely used in the following. It comes from the dispersion relation:

$$\omega^2 = gk \Rightarrow \lambda \approx 1.56T^2 \quad (2)$$

This formulation means that a linear wave is completely described by its frequency and its amplitude in infinite water depth.

Another formulation that should be kept in mind for the following is an empirical limitation for a wave to be considered linear. Physically, a wave cannot remain sinusoidal if its steepness ε ($\varepsilon = H/\lambda$) is too high. Indeed, above a given limit, the waves are breaking. It means that for a given wavelength, there is a maximum height above which waves cannot be considered linear anymore:

$$\varepsilon_{max} = H_{max}/\lambda = 1/7 \quad (3)$$

Now that some clues about what are linear waves are established, some considerations about linear systems can be made. Basically, considering that the ship response to input waves follows linear theory means that:

- All boat responses (heave, pitch…) to a sinusoidal wave excitation of frequency f is also a sinusoid of frequency f. The amplitude of the oscillation is of course not the same. The phase is also not the same.
- The response to a linear combination of sinusoidal waves is the same linear combination of the responses to each sinusoidal wave (superposition principle).

This is depicted in figure 3. This is very strong assumption and means that waves of different frequencies can be studied separately and that the amplitudes can be put aside. Indeed, if the response to a 1m wave of frequency f is known, the response at same frequency for amplitude A is obtained just multiplying by A.

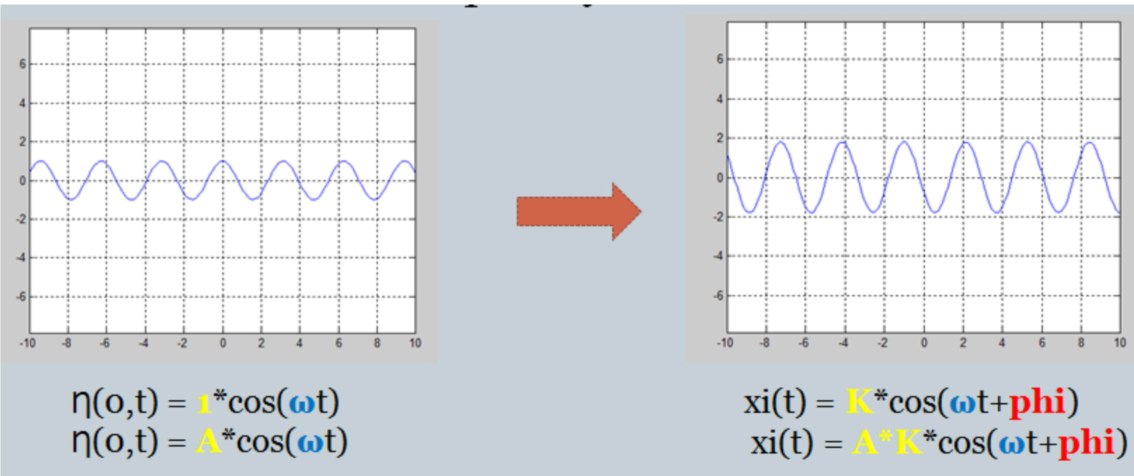

Figure 3. Ship response in linear theory

For a given frequency *f*, the amplitude of the response of a response (heave, pitch…) for a 1m wave is called *RAO(f)* which stands for Response Amplitude Operator. Similar concept exists for phases and is called here *φ(f)*.

The main issue of this work is thus to see how to compute the RAO for pitch motion and how to estimate it quickly. The RAO concept applies not only for the 6 motions but also for the velocities and accelerations. Another issue of this work is to compute the acceleration in the mast RAO.

Moreover, in reality, waves at sea are not perfect sinusoids, but an irregular sea state can be approximate as a linear combination of harmonic waves. The principle of superposition allows getting responses also in irregular sea states.

In the next part is highlighted how *HydroStar* computes the motion RAOs.

3. PRESENTATION OF HYDROSTAR

The aim of this work is to investigate the pitch motion of sailing boats. To understand the motion of a body, one must know what the forces acting on this body are. Dealing with a boat at sea, most of the forces acting on the boat are exerted by water. The fluid properties need thus to be investigated.

3.1. Potential Flow Problem

Water is an incompressible Newtonian fluid which behavior is fully described by Navier-Stokes equations. This set of equations links quantities like fluid pressure (p), velocity ($\boldsymbol{V}$), density (ρ).

These equations are coupled and non linear. They cannot be analytically solved. The computation time needed to solve it is quite high (few hours or days typically for naval issues).

Making some physical assumptions, these equations can be simplified into a new set of equations called potential problem. Namely:

- **The fluid is considered incompressible (constant density $\rho=1025\ kg/m^3$).**
- **The fluid is considered non viscous ($\upsilon=0$). Viscosity effects are therefore always neglected in the following.**
- **The flow is considered non rotational.**
- **The flow is considered periodic (harmonic) at pulsation $\omega=2\pi f$. All the (complex) physical quantities vary temporally in $e^{i\omega t}$ which allows to get rid of time dependence.**

Under that assumptions, it can be shown that it exists a scalar function $\varphi(x,y,z)$ called potential that verifies a new set of equations. This set of equations is still not linear. It is linearized using the hypothesis of small wave steepness ($\varepsilon<<1$) which lead to a final set of equations verified by φ and depending on boundary conditions. It is the first order potential problem:

$$\Delta\varphi = 0 \text{ in the fluid domain } D$$

$$g\frac{\partial\varphi}{\partial z} + \frac{\partial^2\varphi}{\partial t^2} + \rho\upsilon\frac{\partial\varphi}{\partial t} = 0 \text{ in } z=0 \text{ (linearized free surface F)}$$

$$\frac{\partial\varphi}{\partial n} = \vec{U}.\vec{n} \text{ on the hull surface H (slip condition)} \qquad (4)$$

$$\frac{\partial\varphi}{\partial z} = 0 \text{ for } z=-h$$

Where:

- *n* is the normal vector to the ship hull as shown in figure 4. It is known from the hull geometry.
- *h* is the water depth that can be infinite
- *U* is the boundary velocity at the observed point

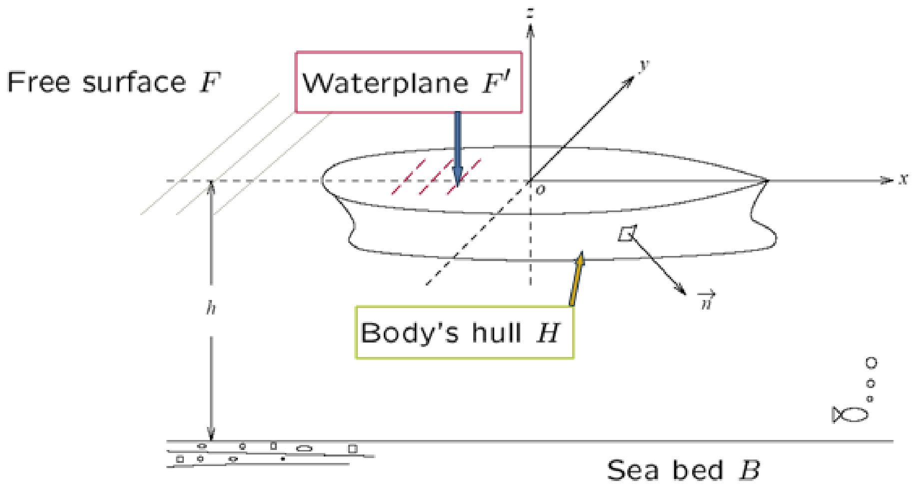

Figure 4. Representation of fluid domain and boundary domains
Picture from *Hydrostar* training presentation by *BV*

It can be noticed here that the body motion (given by $\vec{U}$) and the fluid properties (described by φ) are coupled by these equations. Typically, if body motion $\vec{U}$ is known, then it impacts the flow properties described by φ that can be found. It will generate forces on the hull that will modify $\vec{U}$ and so on.

Notice also that the free surface condition is linearized in z=0. It means that <u>the underwater part of the ship at sea is supposed to be constant</u>, which is a strong hypothesis.

Then, if for a given situation φ is known, then the values of interest can be deducted in any point *(x,y,z)*:

$$\vec{V} = \overrightarrow{grad}(\varphi) \quad (5)$$

Then, from Bernoulli equation the pressure *p* can be found:

$$\frac{\partial\varphi}{\partial t} + \frac{\vec{V}^2}{2} + gz + \frac{(p-p0)}{\rho} = 0 \quad (6)$$

With:

- *g* the gravity acceleration (m/s²)
- *p0* the atmospheric pressure (Pa)

Finally, by integrating pressure on hull surface, the forces acting on the hull can be found:

$$F = \iint_H p \, dS \quad (7)$$

In the following, it will be explained how equation (4) is solved to find φ when $\vec{U}$ is known. Then, it will be explained how to solve the global problem of ship motion in waves using the basic problem described by (4).

3.2. Panel Method

The idea to solve the first order potential flow problem described by (4) is to combine elementary solutions, called *singularities*, to build a global solution. Indeed, a linear combination of potential flow is still a potential flow.

In *HydroStar*, φ is supposed to be a linear combination of elementary potentials *Gi* called green functions:

$$\varphi(x,y,z) = \sum_{i=1}^{N} \alpha_i \, G_i(x,y,z) \qquad (8)$$

with *Gi(x,y,z) = G(xi,yi,zi,x,y,z)*.

G has an analytical description. The *N* elementary potentials *Gi* are located on the underwater hull surface. This is the reason why the underwater part of the hull has to be meshed into *panels*. The center of each panel has the coordinates *(xi,yi,zi)*. All *Gi* verify (4) by default apart from the hull boundary condition. By injecting (8) in (4) the hull boundary condition transforms the problem into a linear system which unknown are the *αi*. As big as this linear system might be, it exists efficient mathematical methods to solve it in few seconds. Once the *αi* are known, φ is known and thus velocity, pressure and forces on the hull can be found.

Up to now, the general idea to solve (4) and how to deduce the physical quantities of interest from it have been exposed. In the following subsections will be explained how to solve the global seakeeping from basic problem (4).

3.3. Equation of Motion: Frequency Domain Approach

The few points exposed about linear theory in part 2.3 express the interest of studying the seakeeping problem for a given harmonic wave excitation at frequency *f* or pulsation *ω=2πf*. Under linear theory it is very convenient to write any physical quantity *x(t)* as:

$$x(t) = Re\left(X_0 e^{i\omega t}\right) = Re(X(t)) \quad (9)$$

With X_0 complex amplitude that does not depend on time anymore. In the seakeeping problem, all variables dependency on time is in the complex exponential and can be simplified everywhere. The information to be found is the complex amplitude, which means real amplitude and a phase.

With this notation, time derivative are easily computed:

$$\dot{X}(t) = i\omega X(t) \quad (10)$$

$$\ddot{X}(t) = -\omega^2 X(t) \quad (11)$$

In seakeeping, the variable *X* of interest is the boat motion. With 6 DOF, it is a vector of dimension 6. It is ruled by the equation of motion that writes in the frequency domain:

$$M\ddot{X} = \sum F = F_{Hydrodynamic} + F_{Hydrostatic} \quad (12)$$

With *M* the *6x6* mass matrix of the ship, which is a diagonal matrix with coefficients equals to the displacement. As weight is cancelled by buoyancy, the hydrostatic force is only the hydrostatic stiffness expressed by the hydrostatic *6x6* matrix which is supposed to be known:

$$F_{Hydrostatic} = -KX \quad (13)$$

The hydrodynamic force has different sources:

- The added mass effect that is proportional to ship acceleration.
- The wave damping proportional to ship velocity (viscous damping is not taken into account)
- The wave excitation force.

It can be written:

$$F_{Hydrodynamic} = [M_A(\omega)\omega^2 + i\omega B(\omega)]X + F_{waves}(\omega) \quad (14)$$

The waves excitation force is itself decomposed into 2 parts: the incident wave and the diffracted wave. Finally, rearranging everything:

$$[-(M + M_A(\omega))\omega^2 - iB(\omega)\omega + K]X = F_i(\omega) + F_d(\omega) \quad (15)$$

This equation has to be solved in *X* for each frequency of interest.

3.4. Radiation and Diffraction Problems

The main unknown in the equation of motion (15) is of course the vector *X* of ship motion. Unfortunately, it is not the only unknown. What is known in equation (15) before seakeeping investigation is:

- The mass matrix *M* and the stiffness matrix *K* from hydrostatics calculations.
- The incident wave excitation *Fi* from wave theory.

The added mass matrix *Ma*, the wave damping matrix *B* and the diffracted wave force *Fd* are not known *a priori*. Before solving (15) for *X*, these 3 quantities have to be found. It is made by decomposing the problem in two different sub problems: the radiation and the diffraction problems.

The radiation problem studies how the movement of the ship is affected by flat water. The problem is actually itself cut into 6 basic problems of 1 DOF. In each basic problem, there is no external wave excitation and the motion of the boat is forced (so is known) along each direction. By solving (4) under these conditions ($\vec{U}$ is known and φ can be found), it allows finding out what are the matrix *Ma* and *B* at the given frequency. Figure 5 illustrates this point.

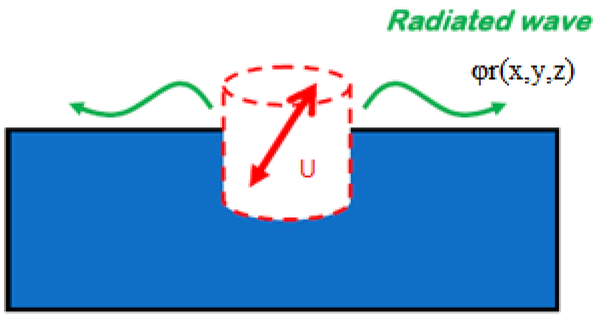

Figure 5. Illustration of radiation problem
Picture from seakeeping class by P. Ferrant at *ECN*

On the other hand, the diffraction problem focuses on a fixed body ($\vec{U} = 0$) in an incident wave field. The aim is to find *Fd(ω)* in (15) by solving (4) under these conditions. This is depicted by figure 6.

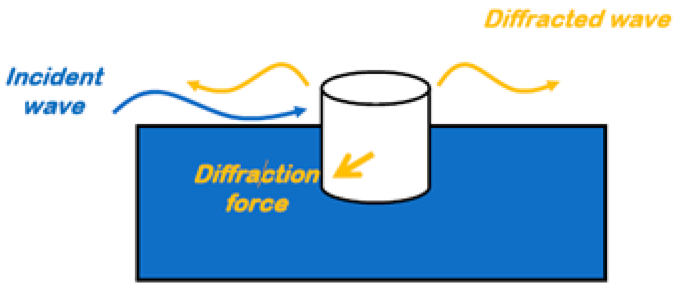

Figure 6. Illustration of diffraction problem
Picture from seakeeping class by P. Ferrant at *ECN*

Following this process, the equation (15) can finally be solved for *X* and the motion computed. If it is done for different wave frequencies of 1 meter wave amplitude, the motion RAOs are then computed.

3.5. Highlights of the Full Numerical Process

HydroStar is very efficient to run the computations of RAOs but it is not very user friendly. It is used in command line and the inputs/outputs are given in text files. Therefore, routines were made in *Matlab* both for formatting the input hull geometry and post-processed the results given by *HydroStar* (RAOs). For the purpose at stake here, the inputs needed by *HydroStar* are:

- the hull geometry. It is required in a given format representing the sections. CAO model of the hulls is made with *FreeShip*, sections are computed and exported. The file format is then modified with a Matlab routine *fromFStoHS* to create *HydroStar* hull format.
- data about the boat (dimensions, mass distribution…). These are given in input text files. The gyration and center of gravity can be directly given or computed from a mass distribution.
- data about regular waves (direction of propagation, frequencies…)

Then a mesh of panels is created within *HydroStar*, the diffraction/radiation problem is solved and RAOs are computed. Then, in *Matlab*, these RAOs are plotted and time series are computed using it. This scheme is represented if figure 7.

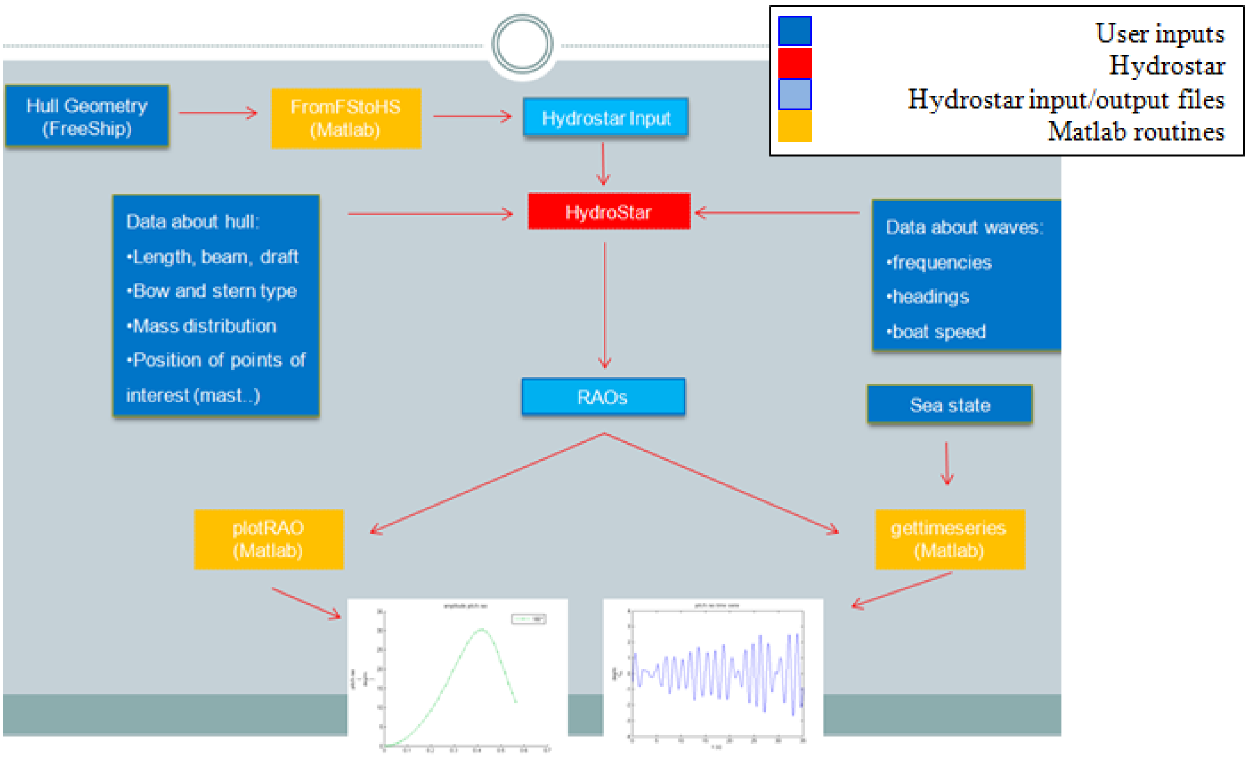

Figure 7. Numerical scheme used in this work

4. PRESENTATION OF THE DATABASE

4.1. Origin and Available Data

The database is composed of 7 **modern** sailing yacht hulls of different lengths from 8 meters to 30 meters. CAO models have been created using the open software *FreeShip*. Basic hull descriptions have been found on the internet (builders' website) where only few data is available. Most of the time, main dimensions (length, beam, displacement, ballast weight) are given and only top and longitudinal views are given.

4.2. Modeling

In *FreeShip*, a basic hull is quickly created from main dimensions. Only the canoe hull body is modeled. Then, the top and longitudinal views are loaded as background images. The hull is modified to fit these views, as shown if figure 8. The draft is given on these views and is thus fixed. Finally, the sections are slightly modified to fit the right displacement.

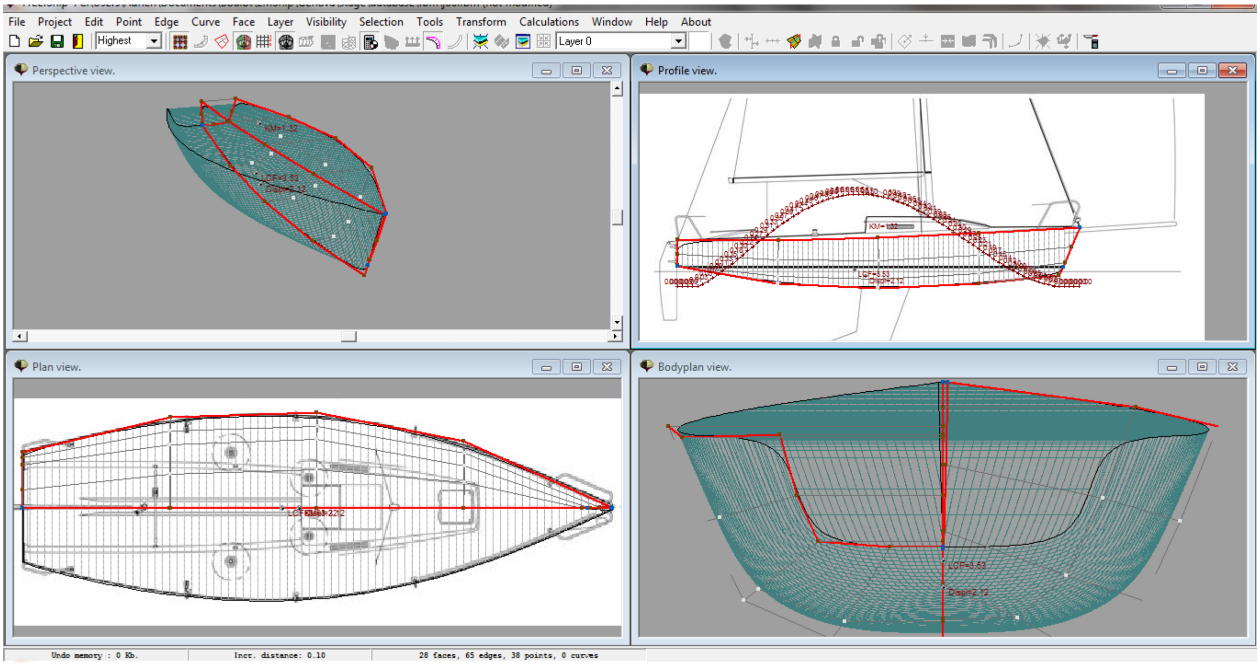

Figure 8. Example of J80 modelling with *FressShip*

Concerning the gyration radius and center of gravity, they are computed by *HydroStar* from an input mass distribution. The input mass distribution is simplified as follows:

- The ballast bulb: its mass is most of the time given by the shipyard on internet. If not, it is evaluated as a percentage of the displacement (35%, usual percentage for this kind of boat). The location of the bulb can be read in *FreeShip*.
- The mast: its mass is evaluated as a percentage of the displacement (1.5%, number given by *RINA*). The mass of the mast is not so big compared to displacement but is important for inertia computation, given the height of the mast. Its center of gravity is taken at half the mast length and can be read in *FreeShip*.
- The canoe hull: its mass is all that remains. It is supposed to be uniformly distributed along ship length. The position of the center of gravity is adjusted to fit a global LCG equal to known LCB and a reasonable VCG (supposing that the boat was correctly built).

4.3. Main Dimensions

Table 1 summarizes the main dimensions of the 7 hulls. Names are referred to with shortcuts. To see full references to hulls see Appendix 1. The pitch gyration radius is written *kyy*.

Table 1. Main dimensions of the 7 hulls

name	LOA (m)	Lwl (m)	B (m)	T canoe (m)	Displacement (kg)	ballast mass (kg)	kyy (m)
SW	31.3	30.4	6.8	1.08	83856	18700	8.70
swan 90	26.8	24.9	6.6	0.95	56726	18400	7.08
oyster 82	24.8	20.9	6.3	1.29	61085	20243	6.33
swan 66	20.3	17.8	5.4	0.90	31030	9400	5.37
ref2	14.5	12.8	4.3	0.66	12877	4507 (35%)	3.63
AME004	11.3	10.3	3.1	0.44	5381	1883 (35%)	2.79
J80	8.0	7.0	2.5	0.34	1825	635	2.11

5. ANALYSIS OF PITCH RAOs

5.1. Formatting of the RAOs

There are different ways to show the RAOs. In this work, it has been chosen to plot the responses for 1 meter of wave in function of the real wave frequency (in Hz). When nothing else is specified, the results are given with the boat with no forward speed and in pure head sea (heading of 180°). Indeed, anyone who has once been onboard a sailing yacht knows that the biggest pitch happens when going in head sea. This choice is also made for simplicity and because it is what is commonly done in literature. Impact of heading and boat speed will be further investigated.

Nevertheless, concerning pitch motion, it can also be interesting in some cases to plot a non dimensional response by dividing response by the wave slope. In this case, the RAO is plotted in function of the wave length. It gives a better understanding of what happens for long and short waves. In figure 9, the 7 pitch RAOs are shown.

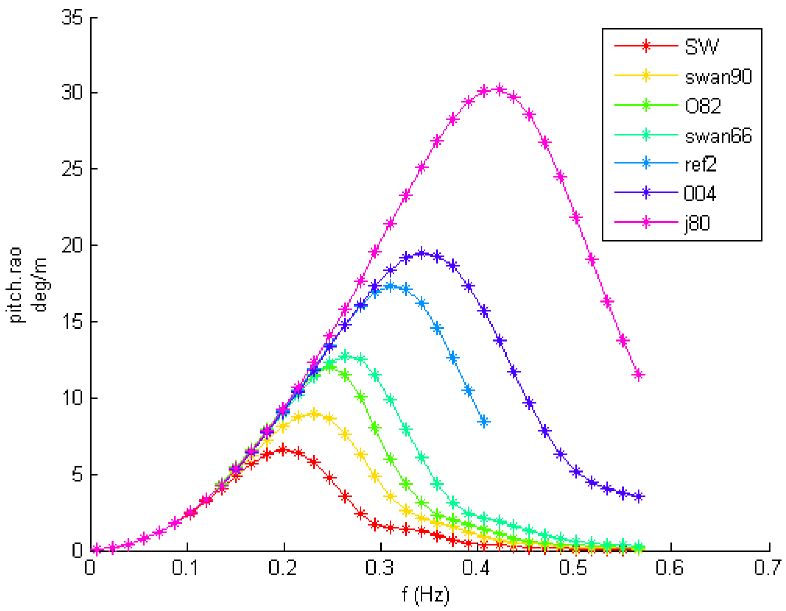

Figure 9. The 7 pitch RAOs obtained with *HydroStar*

It can be noticed right away that for similar hull shapes, the yacht length is a very critical parameter in term of pitching. This justifies why in this part, special focus is given on length only. The impact of some other parameters is quickly studied in parts 8 and 9.

5.2. Comparison with Experimental Results

In [2], the sections and characteristics of a reference hull are given along with some experimental seakeeping results. The idea was then to create a similar hull with freeship and compare the results obtained with HydroStar and the experimental results of the paper. This hull is the hull called *"AME004"*.

This reference hull in the AME CRC series, 004, is an IMS type yacht based on the Delft Systematic Yacht Hull Series II yacht form. A body plan of this reference hull is shown in Fig. 10 and compared with the modeled hull:

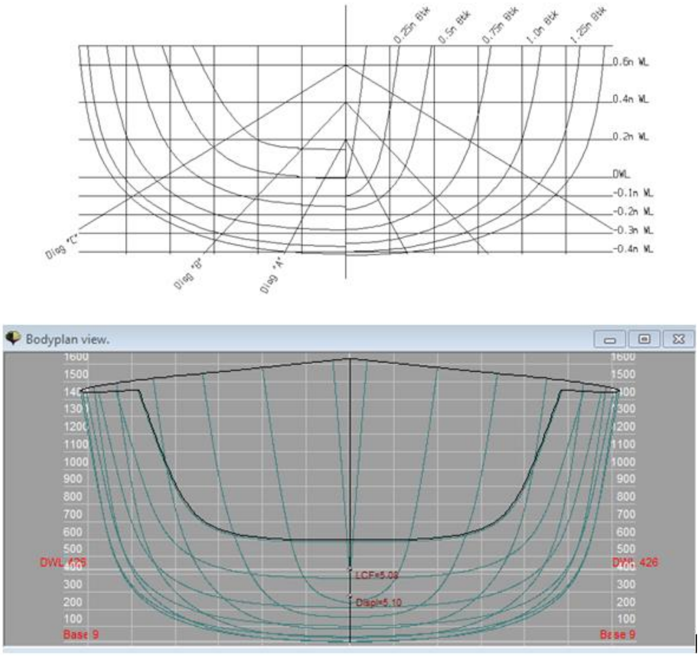

Figure 10. Comparison of AME 004 section lines from [2] (top) and from CAO model (down)

A comparison of the main dimensions of the two hulls can be seen in Table 2:

Table 2. comparison of main dimensions

	paper hull	freeship hull
LOA (m)	11.3	11.3
Lwl (m)	10.23	10.34
Bwl (m)	2.691	2.65
T (m)	0.444	0.444
Disp (kg)	5100	5382
kyy (m)	2.25	3.63

The calculation are carried out with no heel, no forward speed and in pure head sea. The main motions in that case are heave and pitch. The comparison of pitch RAO can be seen in figure 11:

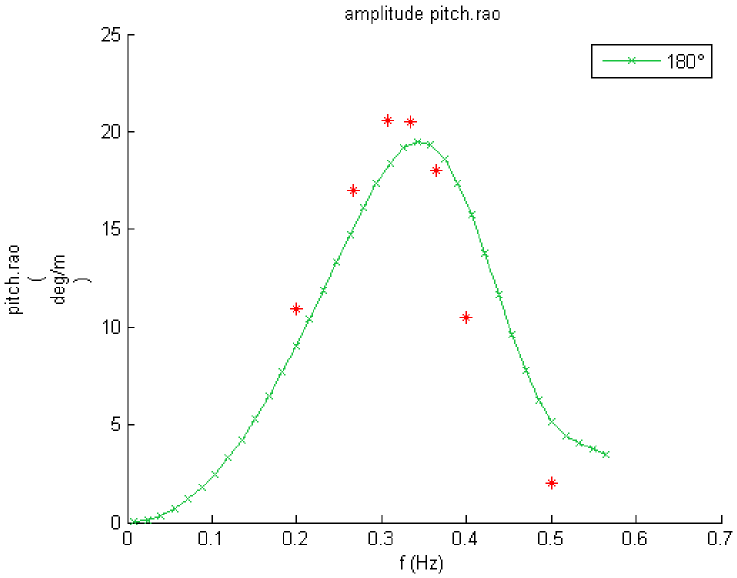

Figure 11. Pitch RAO from *HydroStar* (green) compared with experimental results of [2] (red dots)

Results are similar even if not completely close. This difference is considered acceptable given that the two hulls are not exactly the same.

5.3. Pitch Resonance Frequency in Function of Waterline Length

From figure 9 can be extracted the pitch resonance frequency for each of the 7 boats. From wave theory, in infinite water depth, the wave length can be deducted from the wave frequency thanks to dispersion relation (see eq. (2)).

It is thus possible to plot the resonance wave length in function of the waterline length. As it could be expected from simple physical consideration, the resonance wave length is of the order of magnitude of the waterline length. More than this, results show a strong linear correlation, as shown in figure 12.

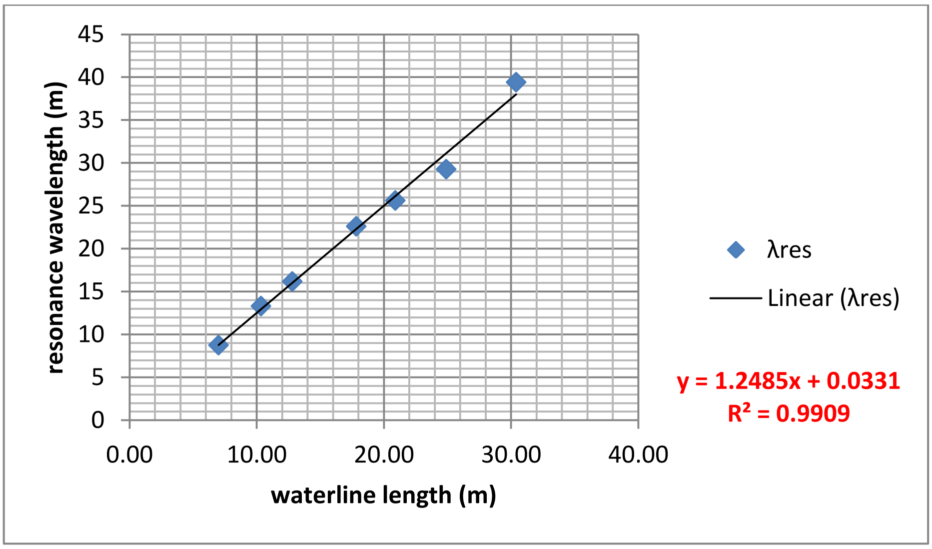

Figure 12. Resonance wave length in function of waterline length and linear interpolation

Therefore, for a modern sailing yacht hull in infinite water depth, with no forward speed and in head sea, the following simplified formula is proposed:

$$\lambda_{res} \approx 1.2485 * Lwl \qquad (16)$$

$$f_{res} \approx 1.118 * \sqrt{\frac{1}{Lwl}} \qquad (17)$$

This formulation is a first try. It would be better to obtain it from more hulls and it needs to be validated.

In the same way, the value of pitch at resonance can be plotted in function of Lwl. The linear interpolation is not so good in that case but other functions may be fitted. An example is shown in figure 13.

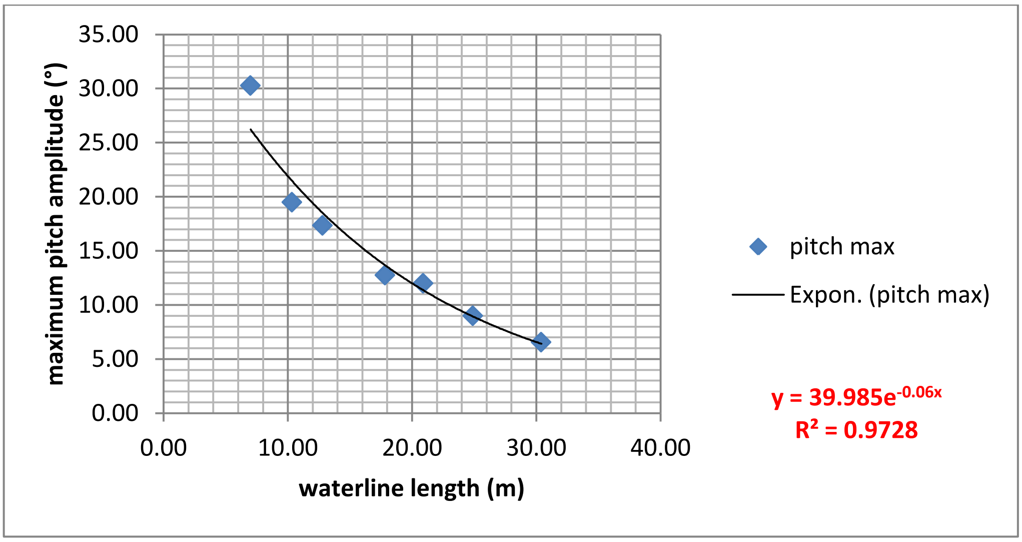

Figure 13. Maximum pitch for 1m wave in function of waterline length

5.4. Wave Length Range of Interest

A common approach to understand RAOs of motions is to imagine the extreme cases of very long waves and very short waves. In short (and thus small) waves, the boat does not 'feel' the effect of the waves. The pitch is 0. In long (and maybe big) waves, the boat follows completely the wave. The maximum pitch is equal to the wave slope ($2\pi/\lambda*a$). This is roughly depicted in figure 14.

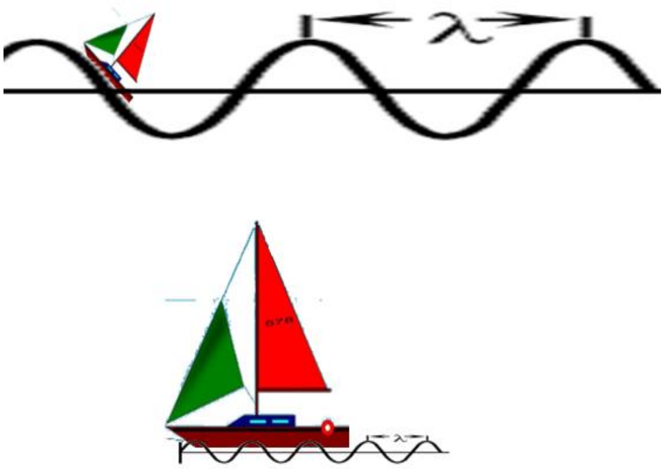

Figure 14. Ship motion in long and short head waves

In term of pitch RAO plotted as pitch over wave slope in function of wave length, it means that the function will tend to 0 in 0 and to 1 in infinity. In the view of a simplified approach of pitch motion, one can divide the pitch RAO into 3 regions:

- under a wave length $\lambda0$ the pitch is almost 0 (for example less that 5% of wave slope)
- above a wave length $\lambda1$ the pitch is almost equal to wave slope (for example 95% of wave slope)
- between $\lambda0$ and $\lambda1$ is the region of interest, where the resonance is (if there is one)

As an example, figure 15 shows the pitch RAO of the boat SW along with $\lambda0$ and $\lambda1$.

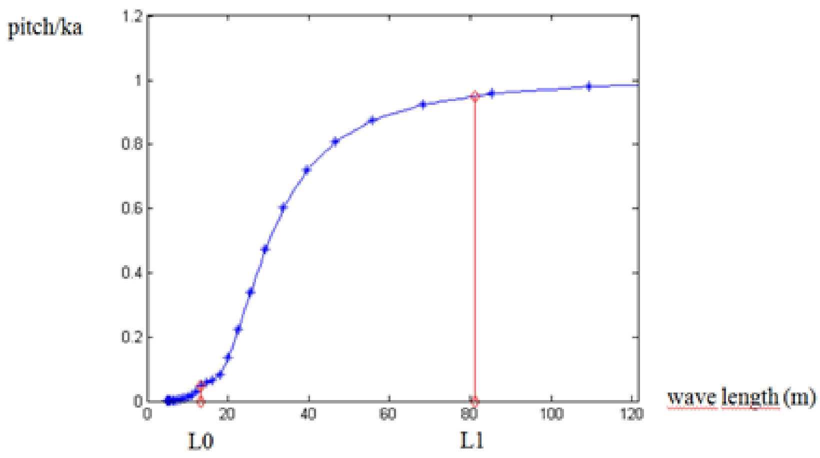

Figure 15. 3 regions of interest on *'SW'* pitch RAO

The values of λ0 and λ1 in function of the waterline length for the 7 hulls are shown respectively in figure 16 and 17.

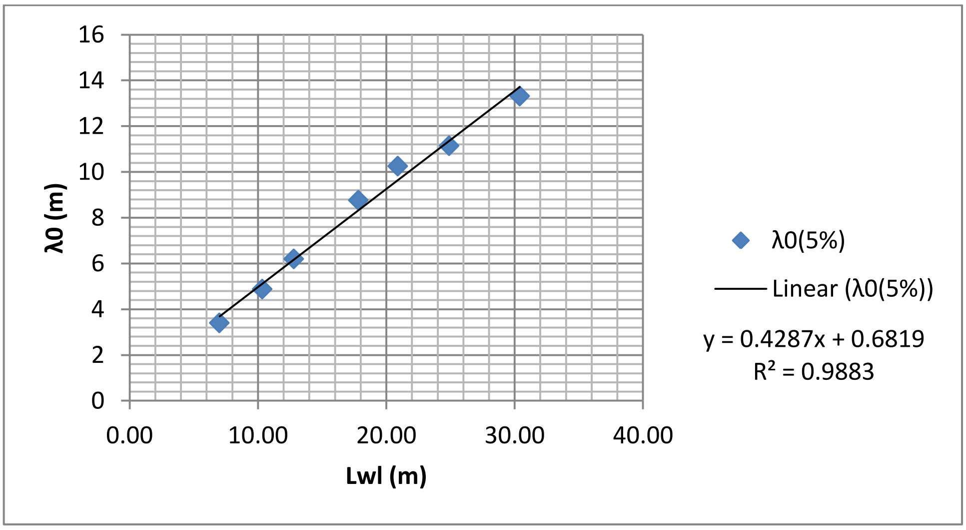

Figure 16. λ0 in function of Lwl

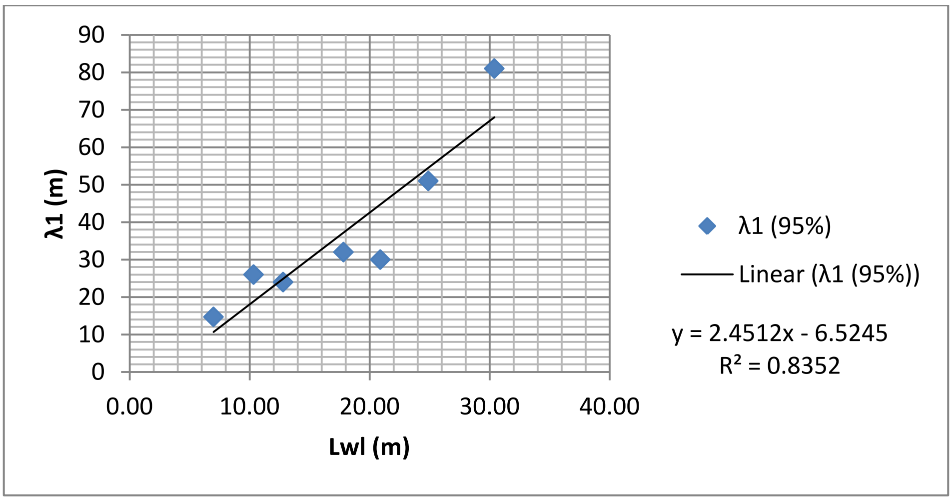

Figure 17. λ1 in function of Lwl

Surprisingly, λ0 shows a good linear interpolation but not λ1. The approximate values of the ratios λ0/Lwl (around 0.5) and λ1/Lwl (around 2-2.5) can be understood by physical considerations:

- when the wave length is smaller than half of the boat length, the boat is always “supported” by at least 2 wave crest which may tend to keep the boat straight (no pitch).
- When the wave length is bigger than twice the boat length, the boat “fits” in half a wave length and can thus follow the wave.

Extreme cases are shown is figure 18.

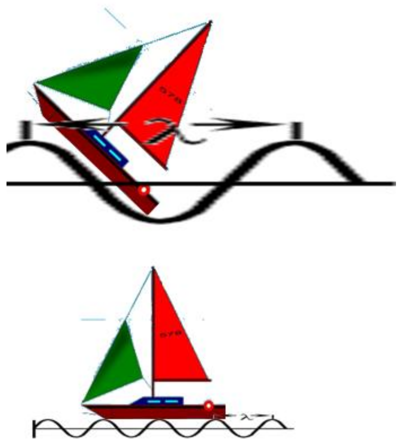

Figure 18. Physical considerations about λ0 and λ1

It can be here assumed that the region of interest of the pitch RAO may be in [0.43*Lwl – 2.5*Lwl] in term of wave length. These results should be investigated on more boats.

5.5. Simplified Pitch RAO

From the previous consideration, a process to get a quick estimation of the pitch RAO of a modern sailing yacht hull is proposed. More investigation would probably allow to get a better tuning for the different parameters. Here are the steps:

- From waterline length, evaluate λ0, λ1 (for example with 0.5 and 2.5*Lwl here) and the corresponding frequencies f0 and f1.
- From waterline length, evaluate λres and the corresponding frequency fres.
- Evaluate also the value of the peak with Lwl.
- For frequencies smaller than f1 (waves longer than λ1), the RAO is estimated with the value of $k=2\pi/\lambda$ (wave slope for 1m amplitude).

- For frequencies bigger than f0 (waves shorter than λ0), the RAO is estimated to 0 (could probably be estimated less roughly).
- In [f1-fres] and [fres-f0], interpolations can be made. Here simple linear interpolations are made.

Figure 19 shows the result of this simplified method on the ship 'swan66'. It is get automatically using only Lwl as input. In that example the peak of the estimated RAO overshoots the "real" one, but it may also be smaller. This result is a bit biased as it is done on a boat which is part of the database used to build the model.

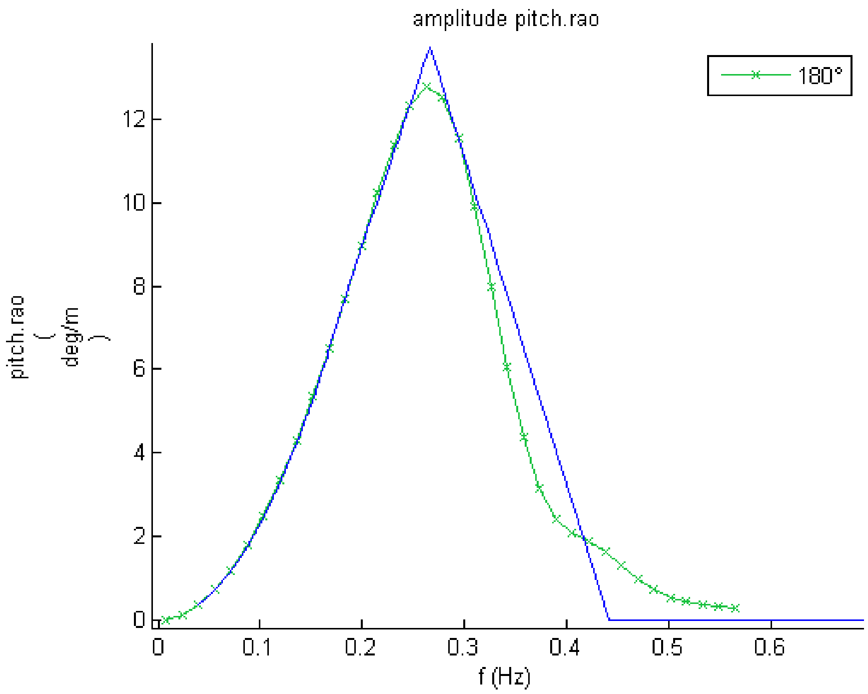

Figure 19. Estimated RAO from Lwl for 'swan66'

In green: RAO computed with *HydroStar*

In blue: estimation with proposed method

s

6. ACCELERATION RAOs

6.1. Acceleration for 1 DOF

The acceleration RAO for a single DOF can easily be derived from the RAO of the corresponding motion. Let $x_i(t)$ be one of the 6 DOF value in function of time. According to the hypothesis of the model used, it can be written, for a wave excitation of pulsation ω:

$$x_i(t) = Re(X_i e^{j\omega t})$$

So the acceleration is easily deduced:

$$\ddot{x}_i(t) = \frac{dx_i}{dt} = Re(-\omega^2 X_i e^{j\omega t})$$

Which means that the acceleration RAO for a single DOF is obtained by multiplying the RAO of motion by ω^2. The phase RAO for this acceleration is obtained by adding π to the one of the motions.

6.2. Motions Coupling

In reality, in a given point of the ship, the total acceleration is due to all the 6 motions. For example, in the case of a ship going head sea, and looking at the longitudinal acceleration in the mast, the 2 most important motions are pitch and surge. Only the longitudinal acceleration is studied, as it is the one suspected to lead to dismasting.

In this simple model, ship is supposed to be a solid body and to rotate around its gravity center. Let us call b_m the distance between the mast center of gravity (taken at mid mast) and the ship center of gravity (see figure 20).

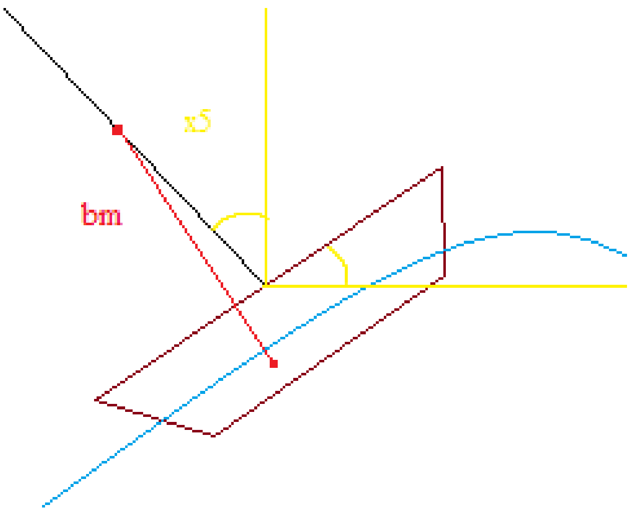

Figure 20. Lever arm at mid mast

Then, the motion of M can be written, with hypothesis of small pitch angle:

$$x(t) = -b_m x_5(t) + x_1(t) \quad (18)$$

$$\ddot{x}(t) = -\omega^2 Re([-b_m X_5 e^{j\varphi_5 t} + X_1 e^{j\varphi_1 t}] e^{j\omega t}) \quad (19)$$

So we see here that with motions coupling, it is not straightforward to get the acceleration RAO. Nevertheless, it is still easy to solve if the information about phases is also available – which is the case with *HydroStar*.

6.3. Comparison of Accelerations in Mast and Cockpit

It can be interesting to compare the acceleration in the mast with the acceleration in the cockpit. This last one is the acceleration felt by the people on board. The perfect case would be to be able to define "working conditions" where the accelerations are sustainable for the mast and for the crew. On the other hand, it might be useless to study the impact of accelerations in the mast that would not be sustainable for the crew. This idea is depicted in figure 21.

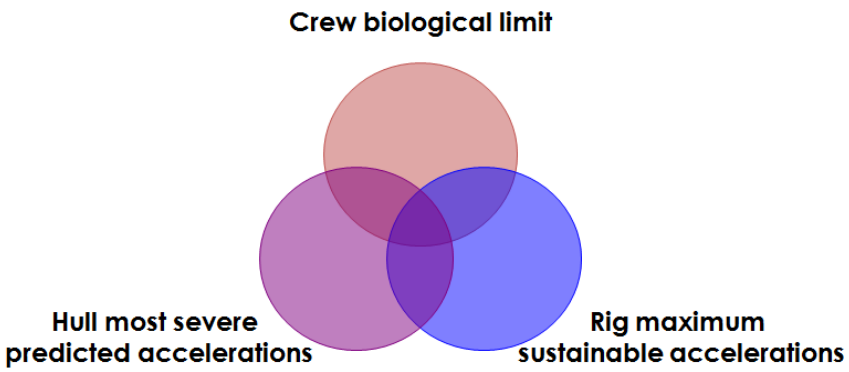

Figure 21 .Different limit of accelerations onboard a sailing ship

For the situation described in figure 20, the acceleration in the cockpit is composed of pitch and heave accelerations. Let us take the example of the 'SW' ship. Figure 22 and 23 show respectively the acceleration in the mast and in the cockpit. Pitch, heave and surge components can be seen. Figure 24 shows the ratio between acceleration in mast and cockpit along with the ratios of the different components.

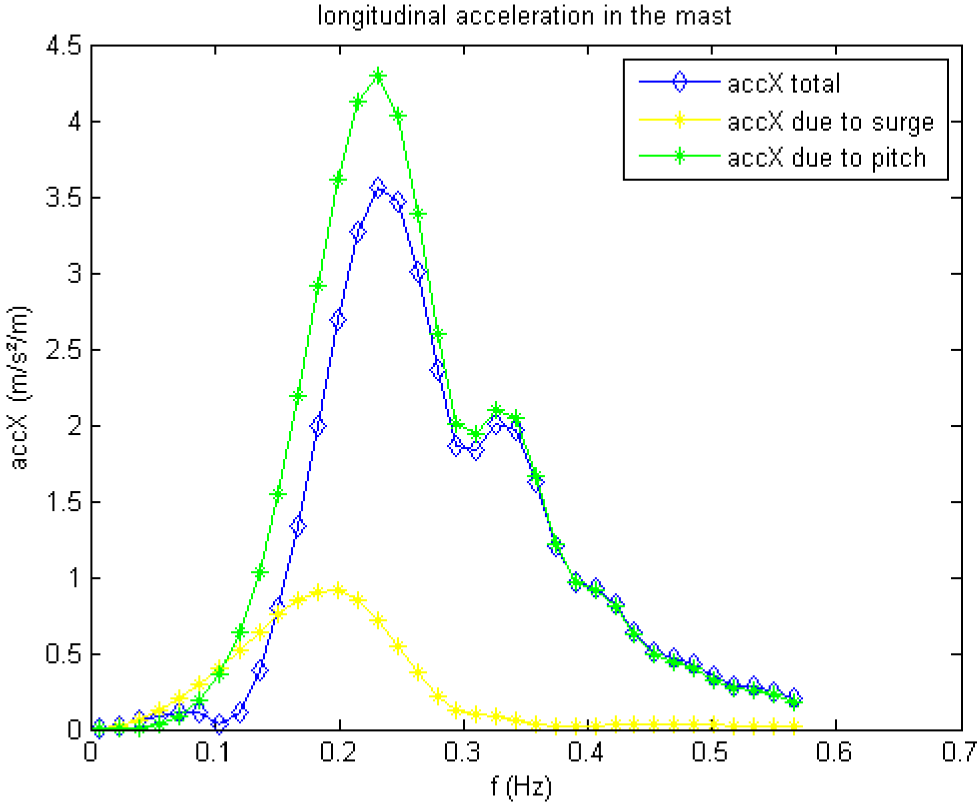

Figure 22. Longitudinal acceleration at mid mast RAO with pitch and surge components

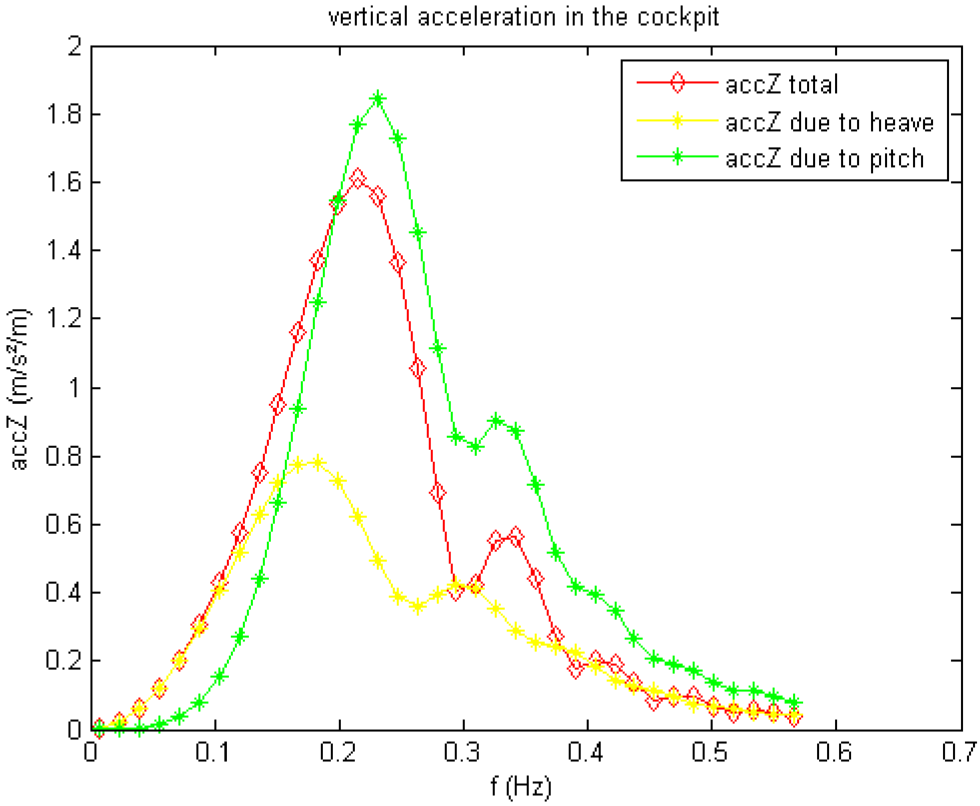

Figure 23. Vertical acceleration in the cockpit RAO with pitch and heave components

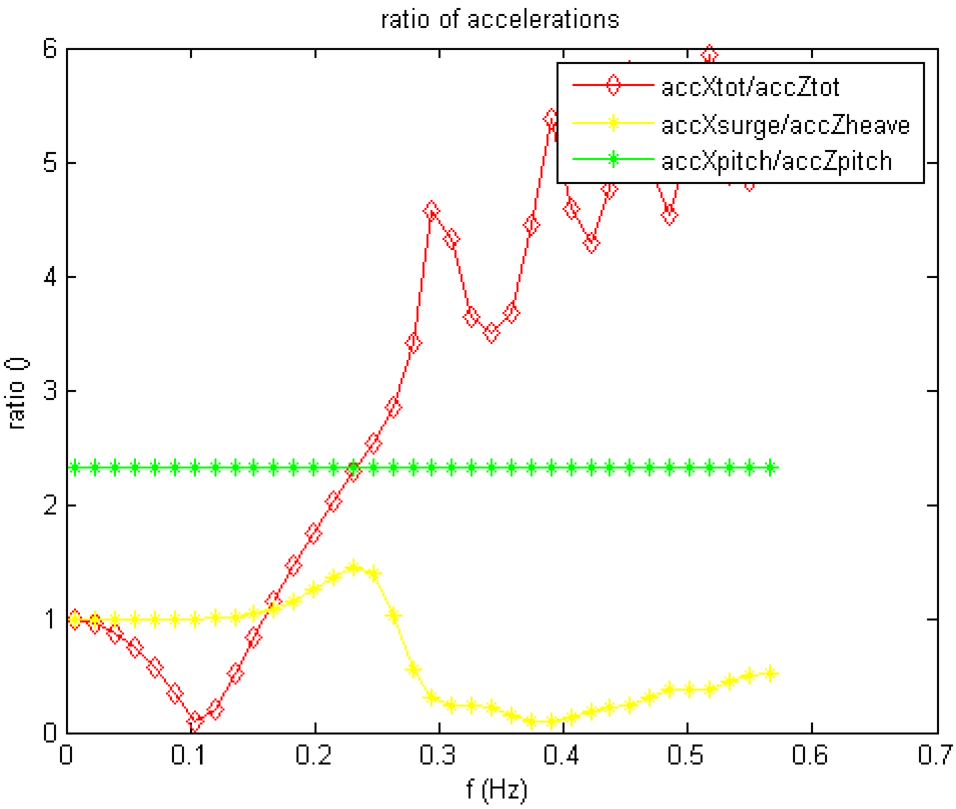

Figure 24. Ratio between acceleration in the mast and in the cockpit and ratios of the different components

Several points can be noticed on this example:

- The surge (or heave) and pitch accelerations are compensating because of phase effects.
- The ratio of pitch accelerations is of course constant and equal to the ratio of lever arms.
- The accelerations resonance frequencies are very close and close from pitch resonance frequency.
- Around resonance, the main effect on acceleration is pitch acceleration. The ratio between acceleration in the cockpit and acceleration in the mast is close to the ratio between lever arms.

6.4. Results on the Database and Quick Estimation of Mast Acceleration

Table 3 shows the acceleration in the mast resonance frequencies for the 7 boats. For bigger boats, pitch is smaller so acceleration is smaller. But for bigger boats, the mass of the mast is also bigger and can lead to important forces. There is thus probably a critical size for which loads may be maximums (as seems to show table 3). An estimation of these forces at resonance is also shown in table 3.

Table 3. Maximum pitch, acceleration and force estimated for 1m wave

As a comparison, the force due to a 20kn wind in the main sail is of the order of magnitude of 10^4N for a boat of the size of 'SW' to 10^3N for a boat like J80.

name	pitch resonance (Hz)	pitch max (deg/m)	accXmast resonance (Hz)	accXmast max (m/s²/m)	estimated mast mass (kg)	force (N/m)
SW	0.199	6.56	0.23	3.6	1257.846	4479.9
swan 90	0.231	9.00	0.26	6.7	850.89	5719.1
oyster 82	0.247	12.00	0.28	9.0	916.275	8257.9
swan 66	0.263	12.76	0.29	10.1	465.45	4698.7
ref2	0.310	17.35	0.36	10.4	193.1535	2004.8
AME004	0.342	19.50	0.41	10.6	80.715	854.2
J80	0.422	30.28	0.47	27.1	27.375	741.9

From previous considerations, here again a rough estimation of the order of magnitude of the peak of the acceleration can be proposed:

- Evaluate pitch resonance frequency and pulsation ω_{res} and maximum of the pitch RAO p_{max} (for example with method exposed in part 5).
- Evaluate the lever arm. For example in the mid mast, it can be roughly be estimated as $\frac{(1.5*LOA)}{2}$
- Evaluate peak acceleration value (for 1m wave amplitude) with:

$$accmax = \frac{(1.5*LOA)}{2} * \omega_{res}^2 * p_{max} \qquad (20)$$

Table 4 shows the estimated maximum acceleration for 1m wave compared to the one computed with *HydroStar*. The estimation is made only with LOA and Lwl. Here again, this values are obtained from the ships used to build the model.

Table 4. Comparison of computed and estimated longitudinal acceleration at mid mast

Name	accXmast max computed (m/s²/m)	accXmast max estimated (m/s²/m)	ratio
SW	3.6	4.29	0.83
swan 90	6.7	6.24	1.08
oyster 82	9.0	8.75	1.03
swan 66	10.1	10.09	1.00
ref2	10.4	13.57	0.76
AME004	10.6	15.11	0.70
J80	27.1	19.39	1.40

The estimation in some cases is quite rough but might be more accurate by inputting more precise data (e.g. the estimation of the lever arm). In other cases the estimation is quite good which might mean that this lead should be investigate more in details. Unfortunately, this approximation is completely irrelevant with forward speed which increases a lot the acceleration as shown in part 8.2.

7. SEA STATE CALCULATIONS

7.1. Theoretical Formulation

The previous results were obtained in regular or harmonic waves. Now in practice, sea free surface is irregular. To solve this, what is usually done in linear theory, is to decompose the free surface elevation in a sum of cosine. This can be written, for a fixed boat at the origin of the axis:

$$\eta(t) = \sum_{i=1}^{\infty} (a_i \cos(2\pi f_i t + \varphi_i)) \qquad (21)$$

The dependence in space vanishes if we consider a boat with no speed.

Waves are supposed to have random phases φ_i. Then, as the problem is linear and solved for regular waves, the response for motion x_i would be:

$$x_i(t) = \sum_{i=1}^{\infty} \left(a_i * \mathrm{RAO}(f_i) * \cos(2\pi f_i t + \varphi_i + \mathrm{RAO}_{\varphi}(f_i))\right) \qquad (22)$$

The RAO used here is the one computed for the heading of interest.

An issue of this time domain approach is how to define the sea state. The problem is thus commonly addressed in the frequency domain. The sea state is often described by a Jonswap spectrum.

$$S_w(f) = \frac{\alpha}{(2\pi)^4} \frac{g^2}{f^5} \exp\left(-\frac{5}{4}\left(\frac{f}{f_p}\right)^4\right) \gamma^{\exp\left(-\frac{(f-f_p)^2}{2\sigma^2 f_p{}^2}\right)} \qquad (23)$$

With $\sigma = 0.07\ if\ f < f_p\ and\ \sigma = 0.09\ if\ f > f_p$

Such a spectrum is completely defined with 3 parameters (see figure 25):

- The significant wave height Hs. It is linked to the area under the curve of the spectrum. It is close to the height a human observer would give by watching the sea. Parameter α is adjusted to fit Hs.
- The peak period Tp=1/fp. It is the period corresponding to the peak of the spectrum.
- The “peakness” factor ɣ. It describes the width of the peak or how the peak is spread over frequencies. Typical values of ɣ are 1 (fully developed sea) and 3.3 (wind sea).

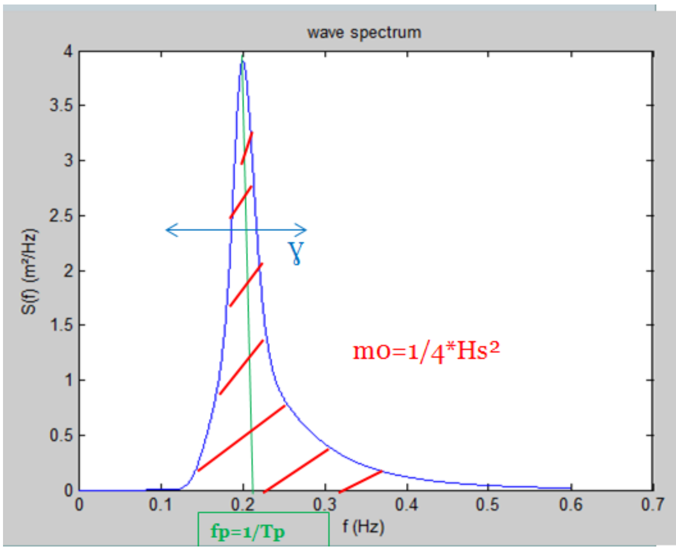

Figure 25. JONSWAP wave spectrum

Then, the spectrum of the motion of interest can be obtained:

$$S_x(f) = |RAO(f)|^2 * S_w(f) \qquad (24)$$

From spectrum, the time series can be reconstructed by:

$$x_i(t) = \sum_{i=1}^{N} \left(b_i * \cos(2\pi f_i t + \varphi_i + RAO_\varphi(f_i))\right) \qquad (25)$$

$$\text{With } b_i = \sqrt{2\Delta f S_x(f_i)}$$

$\Delta f = \frac{f_{max} - f_{min}}{N}$ being the frequency step of discretization.

Now, for a boat with forward speed *U* and a heading β, the assumption of encounter frequency is made. The boat is supposed to stay at the origin of the axis but what is changed is the frequency of the waves it "sees". For a real wave frequency *f* corresponds an encounter frequency *fe*:

$$f_e = f - 2\pi \frac{Uf^2}{g} cos(\beta) \qquad (26)$$

So, for an excitation at frequency *f*, the ship response is no more at *f* but at *fe*:

$$x_i(t) = \sum_{i=1}^{N} \left(b_i * \cos(2\pi f_{e,i} t + \varphi_i + RAO_\varphi(f_i))\right) \qquad (27)$$

In that case, the RAO to be used is ideally the one computed with the heading of interest and at the forward speed of interest.

7.2. Pitch Time Series: Comparison with Experimental Data

Experimental data to be compared with this model are rare. In [3], real on board measurement of pitch motion were performed. The ship is a J80. From personal communication with the authors of [3], some information about the conditions have been obtained:

- Boat was going upwind (40 degrees from wind) at mean speed around 5 knots.
- Wave height was visually evaluated to 0.3m.
- Encounter period was deduced from measured pitch period to 1.3s.
- Measurements have been performed in the bay of Brest, France, which is almost closed basin.

Experimental results are given as a plot of the pitch time series over 35s (see figure 26).

It has been chosen to perform the computation with the following inputs:

- In pure front waves (heading of 180 degrees).
- With a speed of 5 knots.
- In a sea state of Hs=0.3m, Tp = 2.251s (which correspond to encounter period of 1.3s) and with ɣ=3.3 (as the basin is closed, the sea was probably not fully developed).
- No heel angle.

Comparison of time series over 35s can be seen in figure 26.

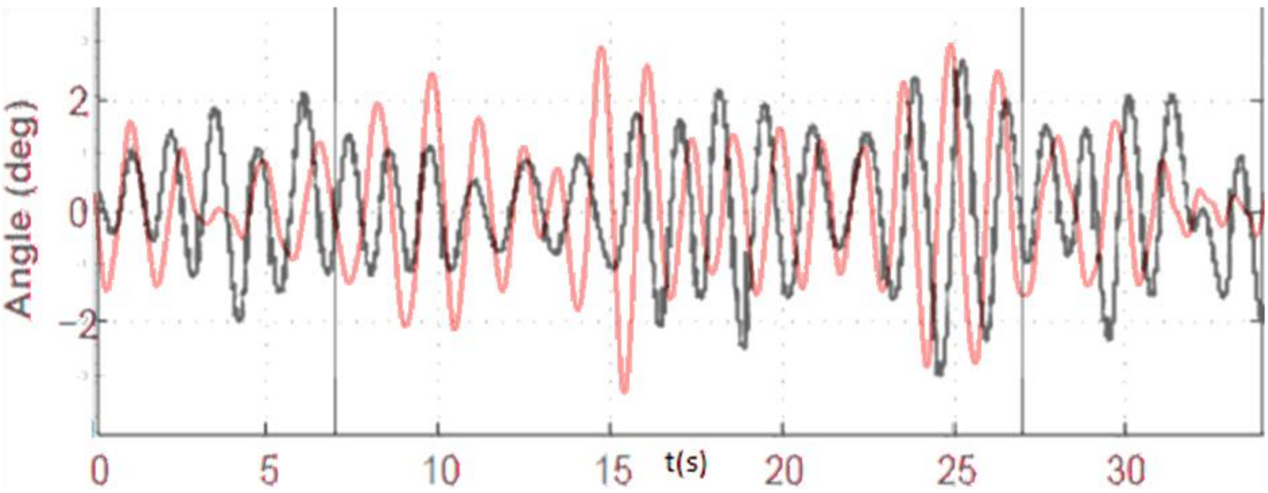

Figure 26. Comparison of pitch time series measured in [3] and computed (Hs=0.3m, Tp=2.25s and ɣ=3.3)

In black: measured data

In red: numerical results

This comparison show very good agreement in term of amplitude and period between the model and the real measurements. It must not be forgotten that there is a random part (the phases) in the computation of these time series. Results will thus not be the same by running twice a computation with the same parameters. It means that the two curves in figure 26 will never superimpose but what matters is the significant height and period of the response.

However, the longest a ship stays on a given sea state, the more likely it is to meet a bigger wave than the average wave. A value that can be recorded is the maximum response staying a given time on a given sea state. As even this value will vary by repeating the same experiment, an average over several similar experiments can be done. This last value would be a bit more robust or "less random".

In the following sub sections, the influence of the 3 sea state parameters on the mean maximum response over 10 similar experiments is studied. Ship is supposed to stay 3 hours on a given sea state (typical duration of a sea state). It is going in head sea with no forward speed.

7.3. Influence of Peak Enhancement Factor

Calculations have been performed for all the 7 ships in four sea states with the same significant wave height Hs=1m and the same peak period Tp=4s. Only the peak enhancement factor ɣ has been changed from 1 to 4.5. Results in term of mean maximum pitch amplitude can be seen in figure 27.

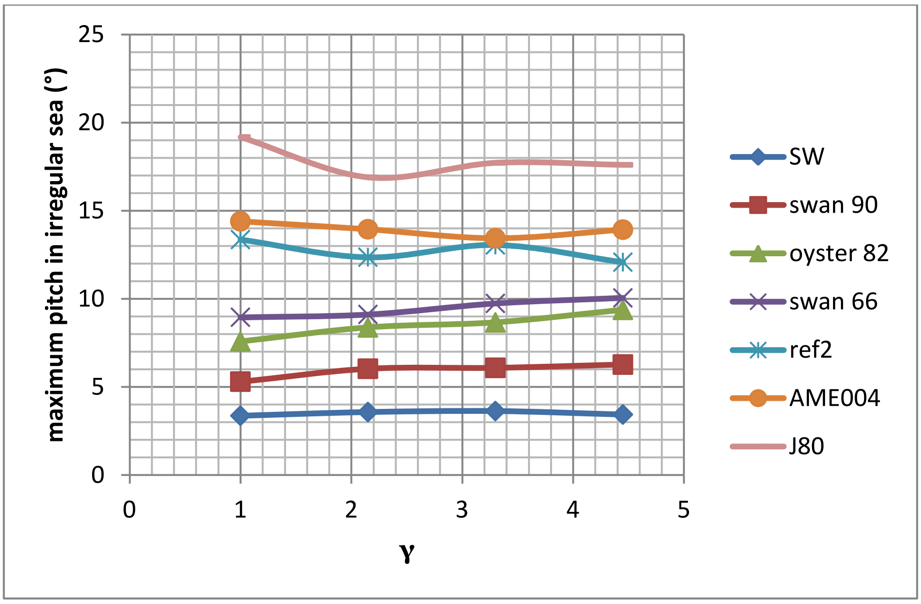

Figure 27. Influence of peak enhancement factor on pitch motion

It can be observed that ɣ does not seem to be a critical parameter. It will thus be taken equal to 1 in the following.

7.4. Influence of Significant Wave Height

In this part, the average maximum pitch over 10 travels on given sea states is again computed. This time, only the sea state parameter Hs is varying (Tp=7s, ɣ=1). In regular waves, with the hypothesis of linearity, the response of the boat would be perfectly linear is wave amplitude (so also wave height). Increasing Hs means increasing the total energy of the sea state. Therefore, it means that the amplitude of each regular wave that composed the sea state will be increased and thus the responses.

What shows figure 28 is that maximum response (here in pitch) in irregular waves are also increasing linearly with wave height, like in regular waves. Taking into account the theoretical model used, it could be expected.

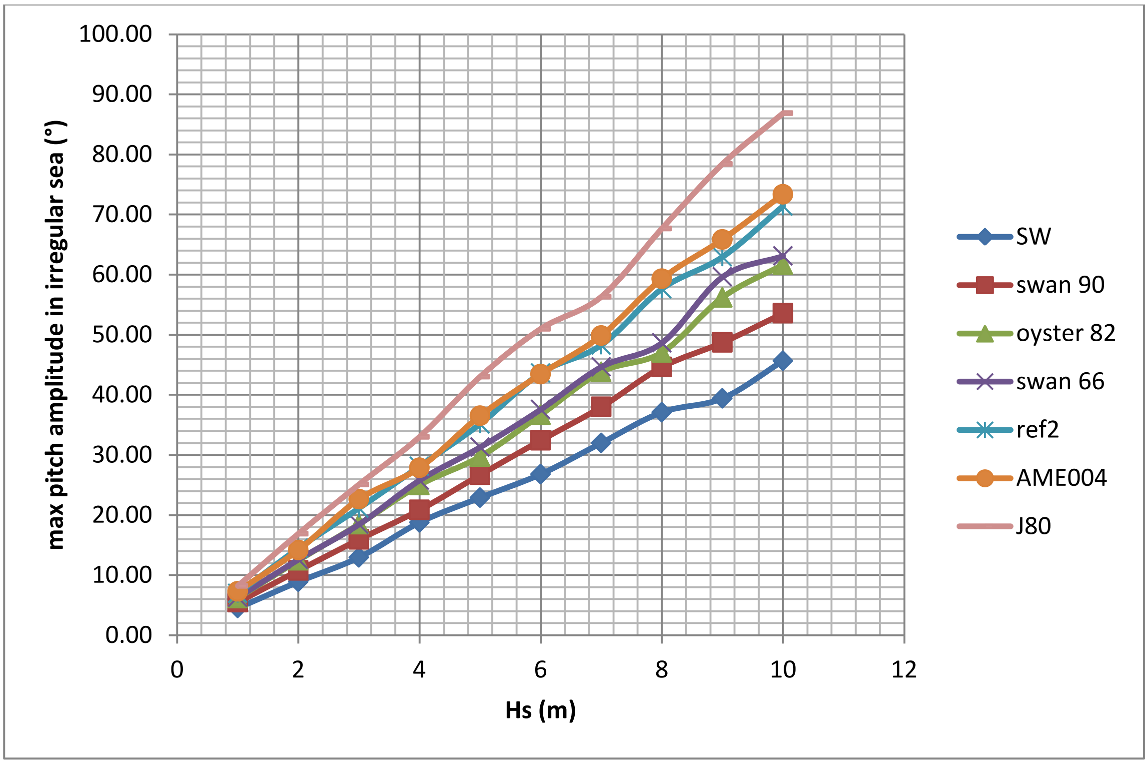

Figure 28. Influence of significant wave height on pitch motion

Consequently, if the value of the maximum response on a sea state of peak period Tp is known, it is known for all the wave heights. Therefore, values of Hs=2m is considered in the following. It is chosen like this for comparing with regular waves of 1m amplitude (i.e. 2m height). In other words, RAOs can be computed for maximum responses in irregular sea.

7.5. Influence of Peak Period: “Irregular RAO”

As explained previously, the average maximum pitch response in different sea states are now computed making only Tp vary (Hs=2m, ɣ=1). It leads to irregular waves RAO in term of average maximum response function of peak frequency.

In figure 29 can be seen the 7 irregular waves pitch RAOs. Same results can be obtained in term of acceleration in the mast, which is shown in figure 30. Finally, it can be interesting to compare regular pitch RAOs with irregular one, which is done in figure 31.

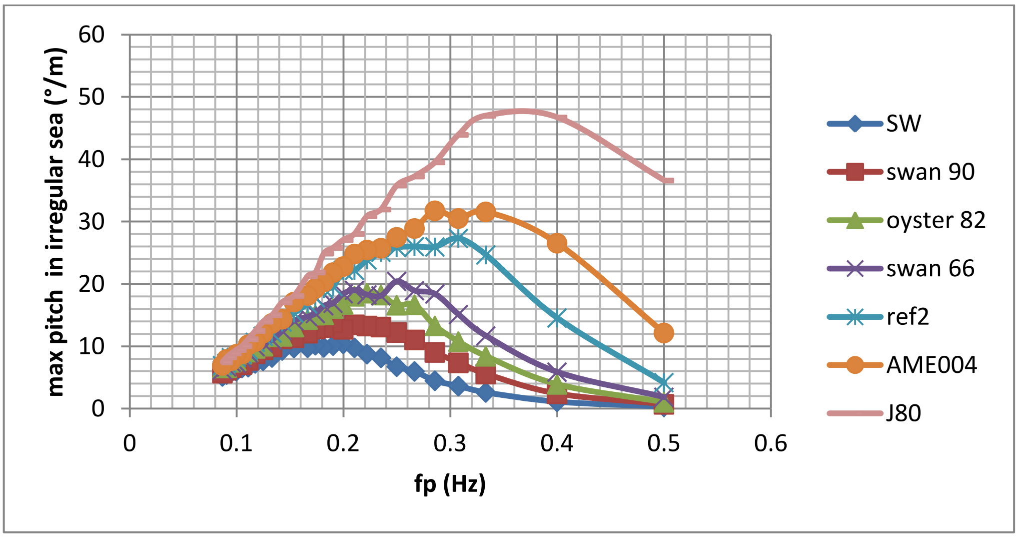

Figure 29. “Irregular sea pitch RAOs”

Mean maximum pitch amplitude for a 3 hours sailing in irregular head sea, with Hs=1m, γ=1 and no forward speed

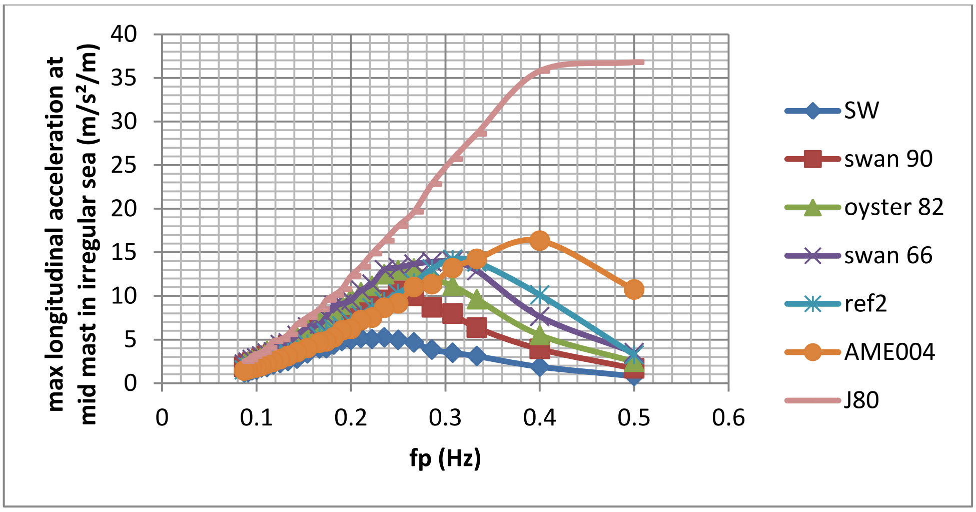

Figure 30. “Irregular sea acceleration in the mast RAOs”

Mean maximum longitudinal acceleration at mid mast for a 3 hours sailing in irregular head sea, with Hs=1m, γ=1 and no forward speed

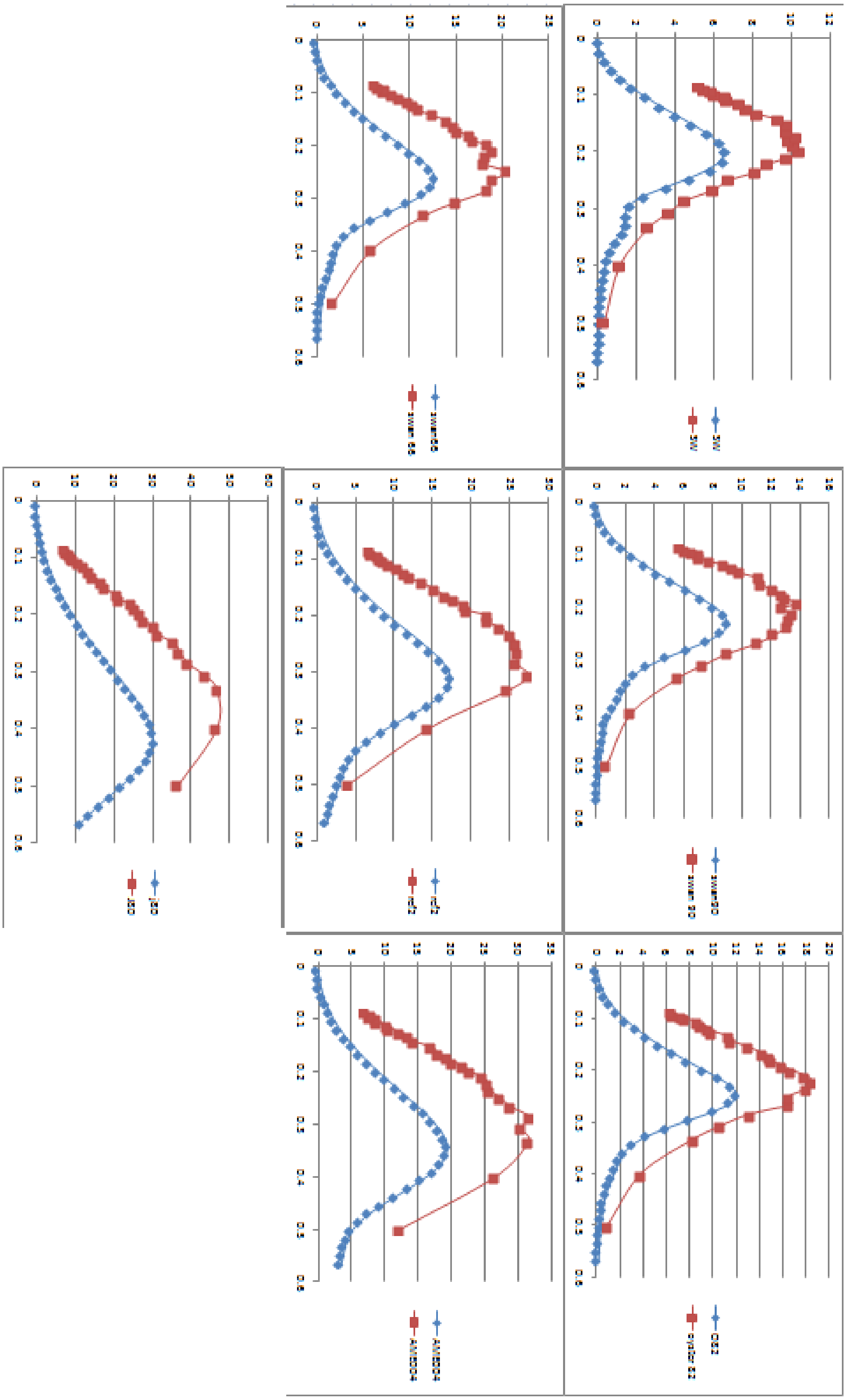

Figure 31. Comparison between regular and irregular sea pitch RAOs

As shows figure 31, irregular seas RAOs overshoot the regular RAOs. Indeed, for a given sea state with Hs significant wave height, the ship is very likely to meet waves significantly bigger than Hs, leading to this phenomenon. In the other hand, it can be seen that the maximum responses are reached when fp=1/Tp is close to ship resonance. Table 5 shows that for a 3 hours travel on a sea state of Tp close to resonance, the maximum pitch can be 60% bigger than the pitch in regular waves.

Table 5. Ratio between maximum pitch in irregular and regular sea

Name	max irregular RAO / max regular RAO
SW	1.59
swan 90	1.54
oyster 82	1.54
swan 66	1.60
ref2	1.57
AME004	1.63
J80	1.55

This factor is not constant over frequencies but still allows a better prediction than the standard RAO. It also depends on the number of waves encountered or the duration of the trip at sea. The example of *'SW'* is shown in figure 32 where the regular RAO is increased of 60% and compared to the sea state results.

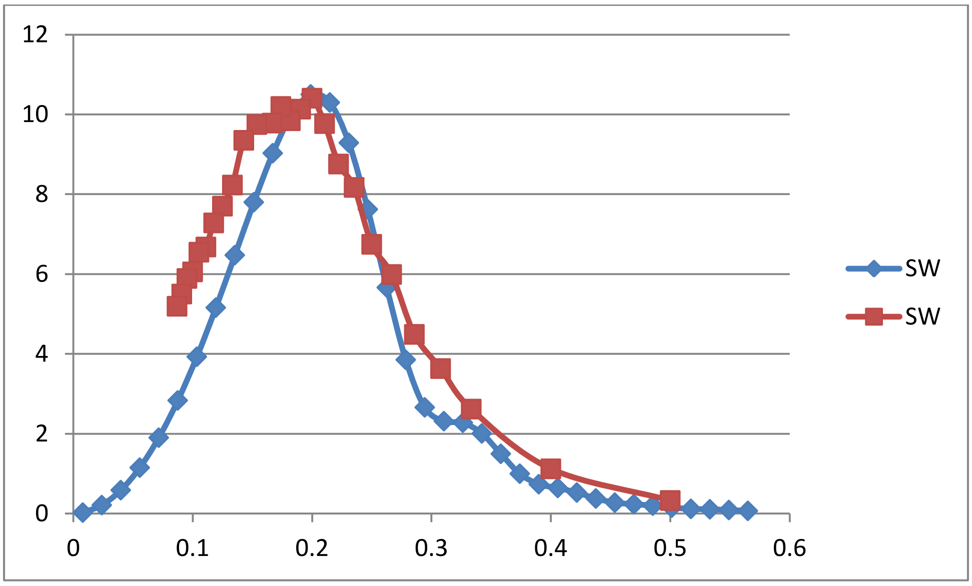

Figure 32. Comparison between irregular sea RAO and increased regular RAO

7.6. About Worst Case Scenario

Being able of defining a worst case scenario that would lead to the biggest ship response would be of great use. Indeed, it would provide the design load for the mast scantling for example.

In linear theory, both frequency and wave height have a big influence on ship motion. At a given wave height, the worst response is of course reached at resonance. Nevertheless, big waves far from resonance can lead to bigger response than small waves at resonance. So, which one will be the design wave?

Ideally, to determine what the worst possible response is, a relation between wave height and wave frequency would be needed. If a function *Hs(fp)* was to be obtained, it could be multiplied to the irregular RAO (or more roughly to the regular RAO increased of 60%) which would give the maximum possible response in irregular sea.

Such a relation *Hs(fp)* is not straightforward to obtain as it depends on a lot of parameters. Empirical link between wave height and wave period can sometimes be found depending on the location (e.g. north Atlantic [1]). So it is possible to imagine getting such a relation that would of course depend on the program of the ship.

Without it, a theoretical relation *Hs(fp)* can also be imagined. As the hypothesis of the model is linear, the most critical linear case can be described. Indeed, the limit of wave breaking (which is obviously not linear) is (recall eq. (3)):

$$\frac{Hmax}{\lambda} = \frac{1}{7}$$

This leads to:

$$Hmax = \frac{0.22}{f^2} \quad (28)$$

This relation is easy but quite limited for several reasons. First it is purely theoretical and may have nothing to see with the effective waves encountered by the ship. Then, and this is true for the general idea of a worst case scenario, the biggest ship response is very likely to happen in a non linear case. Nevertheless, the values predicted with a linear model might be of a correct order of magnitude even for events out of the linear range (e.g. breaking waves with $H/\lambda > 1/7$).

As an example, figure 33 and 34 illustrate this approach in regular waves respectively for pitch motion and longitudinal acceleration in the mast for the ship *'swan66'*. As we can see on these plots, the maximum wave height at low frequencies gets really big, which may be irrelevant compared to real waves met by the ship.

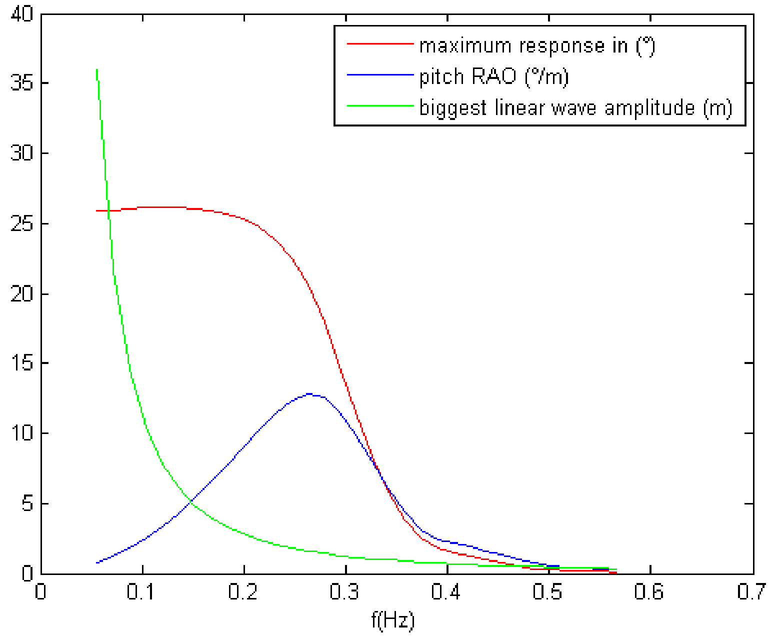

Figure 33. Worst pitch in linear waves

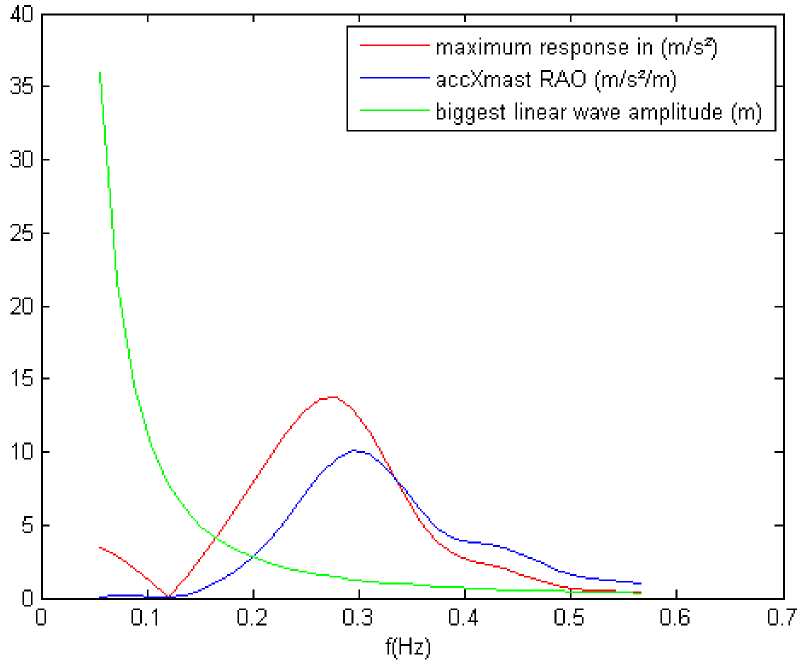

Figure 34. Worst longitudinal acceleration at mid mast in linear waves

On these examples, the orders of magnitude for pitch and acceleration in the mast look realistic but more investigation and comparison with experimental results are needed. It can be noticed that in this simple formulation, the worst response is not reached exactly at resonance.

8. INFLUENCE OF SOME PARAMETERS ON PITCH MOTION

In part 5, the influence of yacht length is studied in details. In this part and in the next one, a quick study of the influence of some other parameters is made on some examples. Special care has been given to length influence not only because it is the most critical parameter, but also because in case of modern sailing boat hulls, a lot of other boat dimensions can be linked to boat length.

8.1. Influence of Pitch Radius of Gyration

Typically, for modern sailing boat, the pitch radius of gyration is in the interval [0.25Lwl-0.35Lwl]. Table 6 shows the ratio between the pitch gyration radiuses computed from simplified mass distribution described in part 4.2 and ship waterline lengths.

Table 6. Ratio between pitch gyration radius and waterline length

name	kyy/Lwl
SW	0.29
swan 90	0.28
oyster 82	0.30
swan 66	0.30
ref2	0.28
AME004	0.27
J80	0.30

Therefore, the impact of pitch gyration radius varying in this range should be studied. It can be expected that gyration radius will change the maximum value of the pitch RAO and also the value of the resonance frequency. Making the analogy with a simple spring, it can be expected that with bigger gyration radius (i.e. bigger inertia) the resonance frequency should decrease (as it is linked to the ratio stiffness over inertia). On the other hand, the peak at resonance should be bigger. Figure 35 shows the pitch RAO of the *'swan66'* for different pitch gyration radius. The resonance does not look to change much in this range of *kyy*. Figure 36 shows the same result but compared to wave slope in function of wave length.

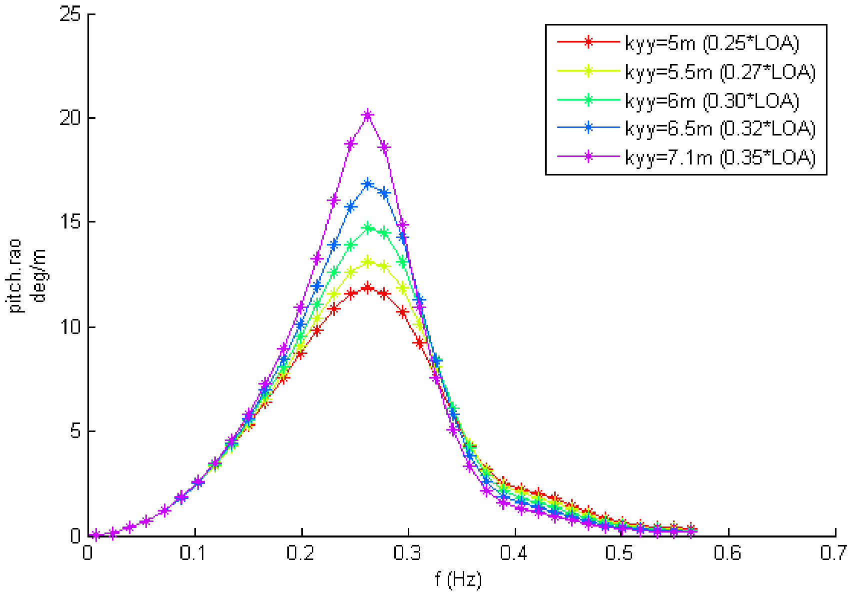

Figure 35. Influence of pitch gyration radius *kyy* on 'swan66' pitch RAO

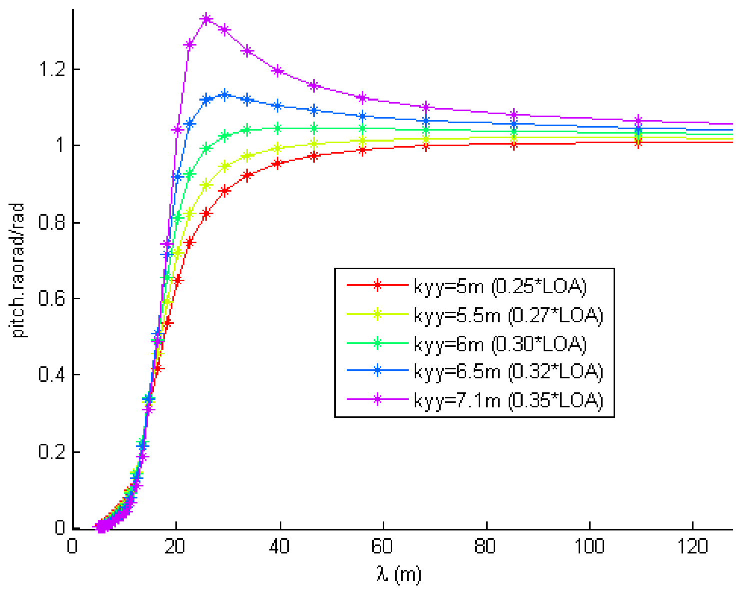

Figure 36. Influence of pitch gyration radius *kyy* on 'swan66' pitch RAO plotted in function of wavelength

It can be noticed that the motion is the "range of interest" between λ0 and λ1 is quite sensitive to *kyy*. On the other hand, out of this range, results are quite similar. The estimation of the RAO in the range λ0 - λ1 might thus be refined using the value of *kyy* in some way.

8.2. Influence of Forward Speed

Up to now, computations have been made with no forward speed for convenience and simplicity. In practice, of course, the yacht has a forward speed. The best case is to have the polar diagram of the ship to be studied to perform a detailed computation at a given speed and heading.

Without it, it could be imagined to define a typical speed for a sailing yacht going upwind that would depend once again on the boat length. Generally, going upwind, a sailing yacht does not go to planning. The Froude number is thus limited to a maximum of 0.4. This gives a maximum speed going upwind. Typically, according to private discussion with M Faloci, a sailing boat going upwind is considered to go 80% of this maximum speed (because of waves for example). Then:

$$U_{typical} = 0.8 * 0.4 * \sqrt{g * Lwl} = 1.0 * \sqrt{Lwl} \qquad (29)$$

Anyway, the effect of forward speed is double. First it changes the equations to be solved by changing the boundary conditions (see eq. (4)). Then, it affects on the encounter frequency. Indeed, if the wave is at frequency *f* the boat "sees" and responds at the frequency *fe* (eq. 26):

$$f_e = f - 2\pi \frac{Uf^2}{g} cos(\beta)$$

Where:

- β is the heading (head sea=180°).
- *U* is the forward speed in m/s.
- g is the acceleration of gravity m/s².

The effect of increasing forward speed in head sea for the ship *'SW'* is shown on figures 37 and 38 respectively on pitch and longitudinal acceleration in the mast. For information, $U_{typical}$ for *'SW'* would be around 11 knots.

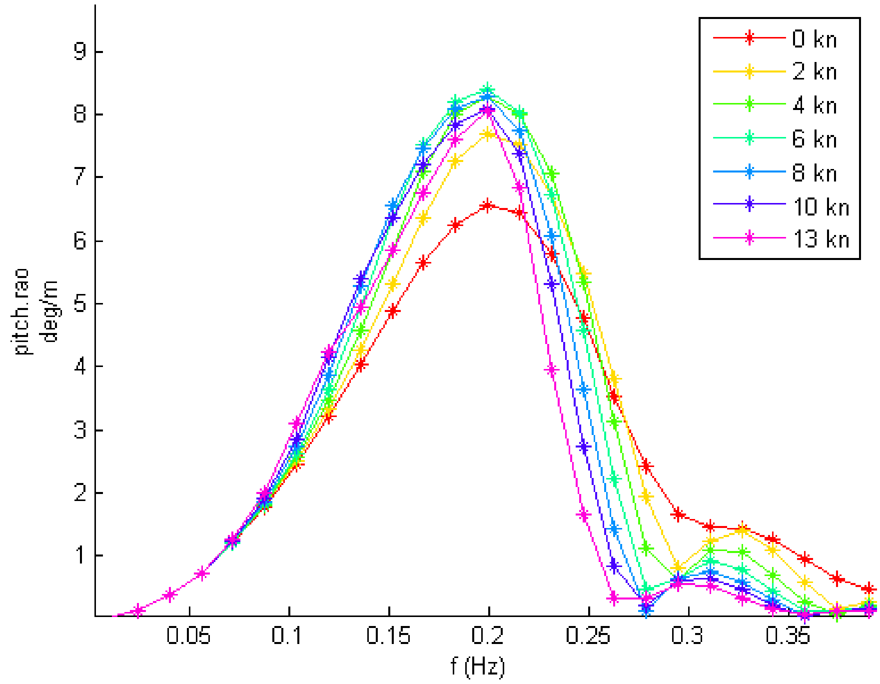

Figure 37. Influence of forward speed on ‘SW’ pitch RAO

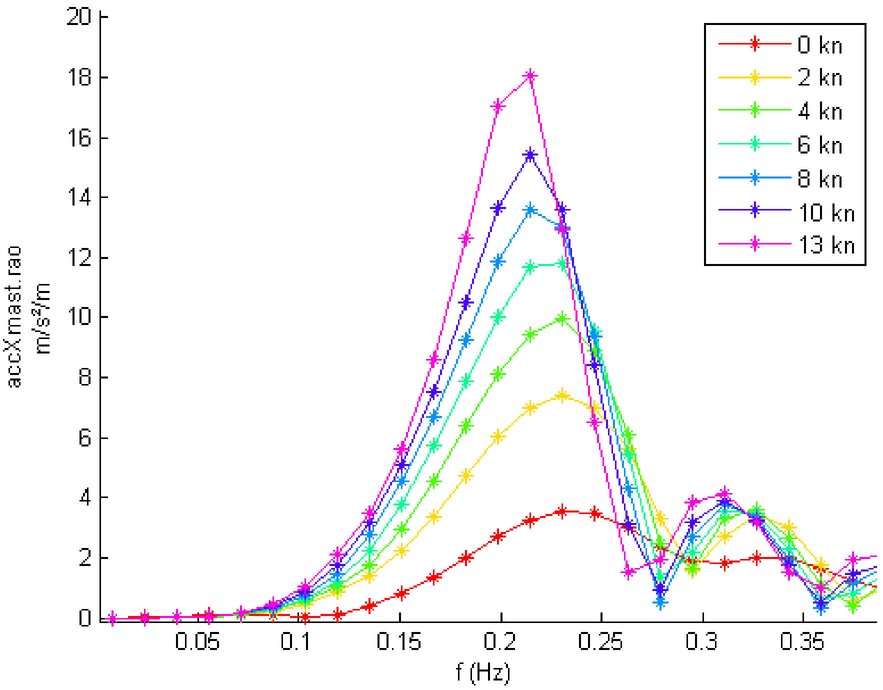

Figure 38. Influence of forward speed on ‘SW’ acceleration in the mast RAO

The forward speed effect on pitch is not so big (+28% around 10 knots) whereas it is huge for acceleration in the mast (4.3 times bigger at 10 knots than 0 knot). It seems logical if thought that, in a way, for a given wave, the ship has to do the same pitch but quicker at 10 knots than 0 knot.

These results may convince to research into the direction of a voluntary speed reduction plan to avoid too big inertial load in the mast (at least when going head sea). Going down wind, and thus more in following sea, the problem is very different. Actually, in headings close to 0 degree (pure following sea), the pitch RAOs are very similar than going head sea. The big difference in that case is the encounter frequency that is much lower. As the boat follows the waves, they look longer and the accelerations are smaller (see part 10 for a detailed example).

8.3. Influence of Heading

Up to now, only motion in pure head sea (heading of 180°) has been considered. It is justified by the fact that the maximum pitch happens when going up sea (which is generally also upwind). The pure head sea (heading of 180°) has been chosen for simplicity. It is not exactly the worst case in term of pitching, as shows figure 39.

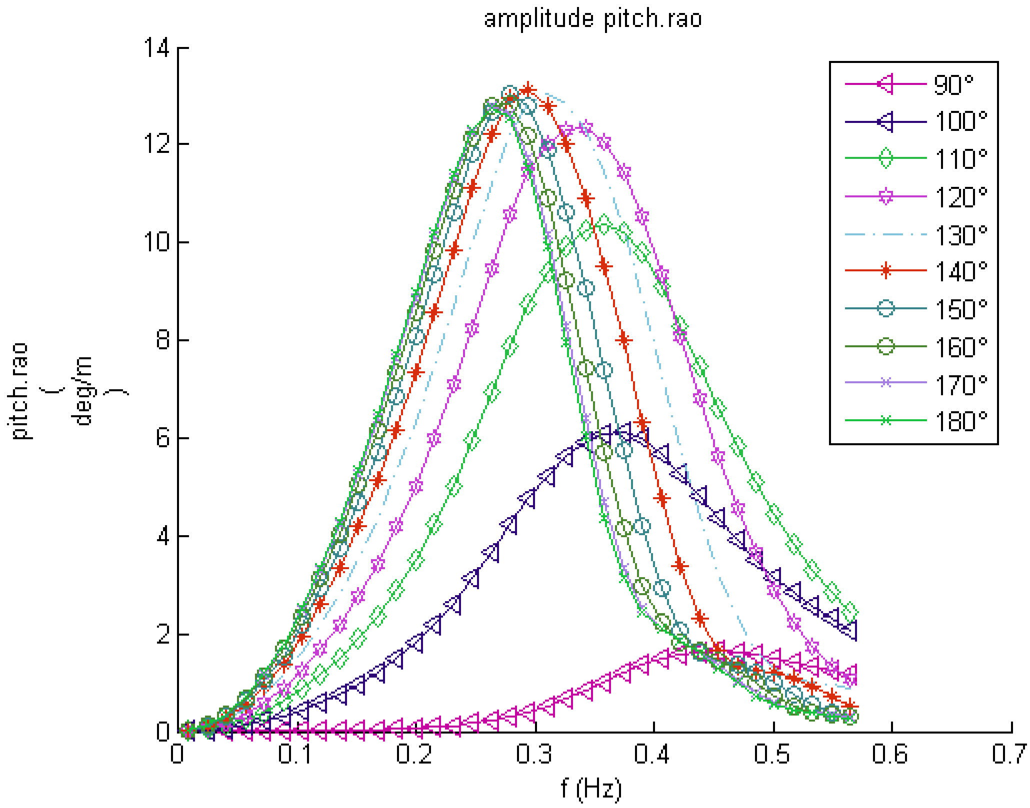

Figure 39. Influence of heading on ‘swan66’ pitch RAO

Nevertheless, around 180 degrees RAOs are quite close to each other and really decrease around 90 degrees (side sea). In some cases, pitch can be bigger around 140-120 degrees.

8.4. Influence of Heel Angle

When going in head sea, a sailing yacht is usually also going upwind. In that case, the wind force leads to significant heel angle which might alter the pitching behavior of the yacht. Figure 40 shows the pitch RAOs of the *'SW'* for different heel angles (from 0 to 20 degrees).

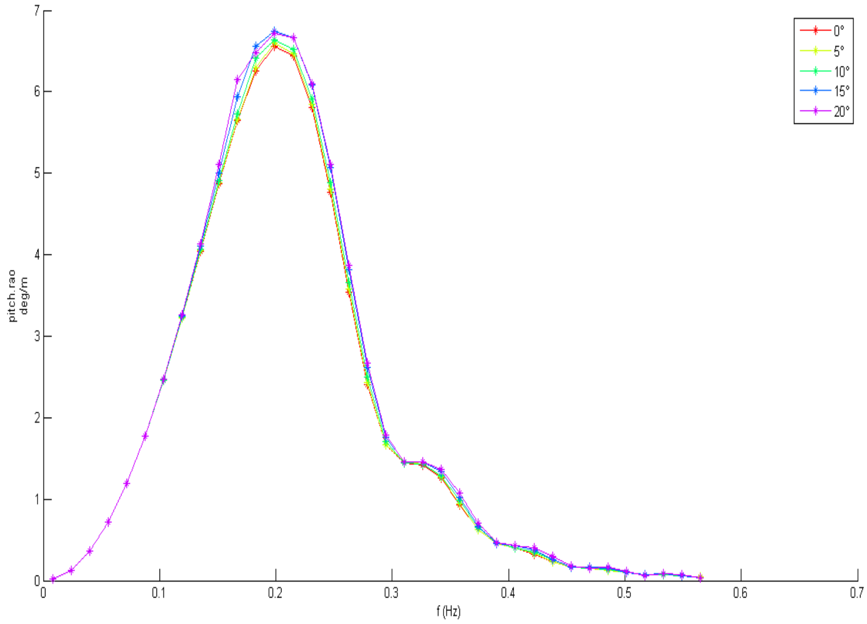

Figure 40. Influence of heel angle on 'SW' pitch RAO

In that case, heel angle is obviously not a critical parameter concerning pitching. It can be explained by the fact that, for such modern sailing hull, the underwater part does not change so much with heel angle.

8.5. Influence of Keel

In all the previous computations, only the canoe hull has been modeled. Indeed, keel is quite long to model whereas its effect on pitching should be small, given that viscous effects are not taken into account.

To confirm that feeling, an example has been carried out on *'SW'*. The modeled keel can be seen on figure 41 and its effect on pitch RAO on figure 42.

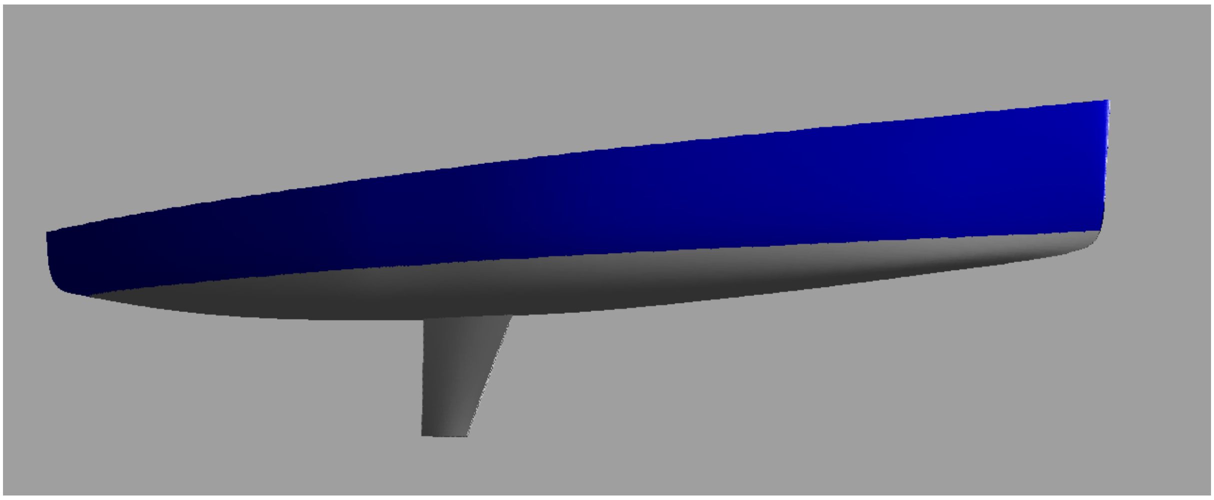

Figure 41. ‘SW’ CAO model with keel

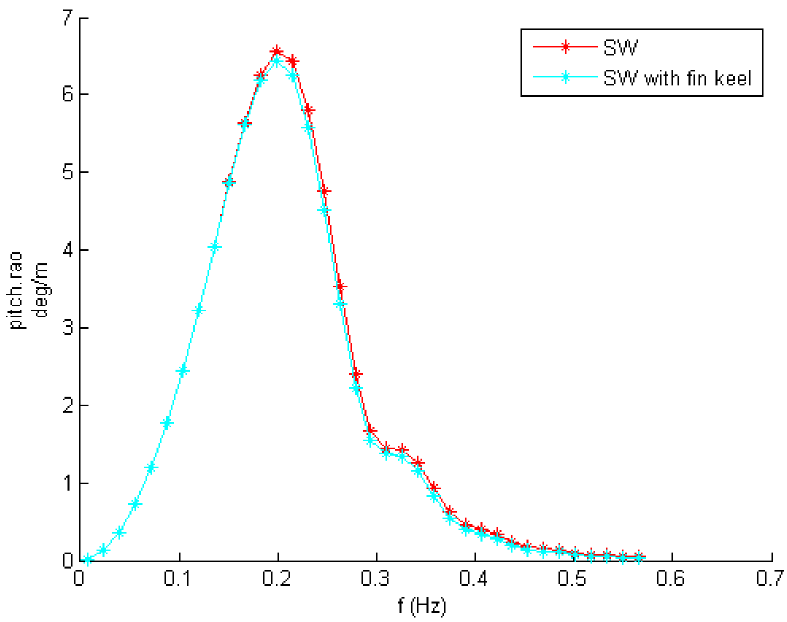

Figure 42. Influence of keel on ‘SW’ pitch RAO

As expected, the effect of such a keel on pitch motion may be neglected. Note that in case of a big heel angle, the effect of keel might be a bit bigger.

8.6. Influence of Water Depth

A significant part of the reported dismasting happened when the ships were getting closer to the coast. This led to the question if it might be because of reducing depth effect. In this purpose, calculations have been performed on *'SW'* for different water depths. Up to now, infinite depth has always been considered. Figure 43 shows the results for pitch RAOs. The smallest water depths used (5m and 2m) might be irrelevant practically and theoretically but were performed to see if a tendency appears.

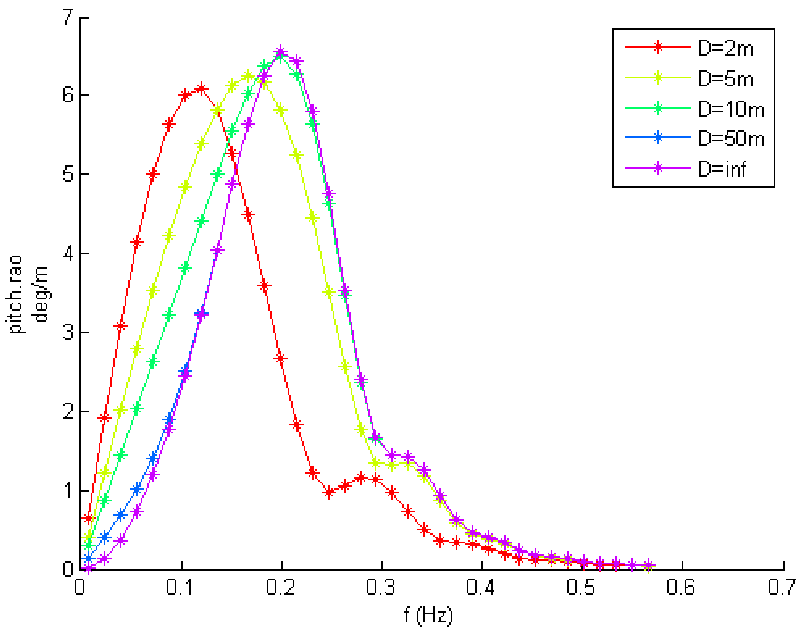

Figure 43. Influence of water depth on 'SW' pitch RAO

A real difference in pitch RAOs seems to appear only for really small depths and tends to decrease the motion. The depth in itself does not look to be a critical factor. More likely, what can explain that dismasting happens close to the shore is the wave frequency. Indeed, waves close to shore may be shorter (so potentially closer to ship resonance) for example as a consequence of smaller fetch.

8.7. Influence of Center of Gravity Position

The position of the center of gravity is not always exactly known. For example, concerning the 7 hulls of the database, it was not known at all and was guessed. Indeed, the longitudinal centers of gravity of the hulls alone have been adjusted to get a global (with mast and ballast) LCG equal to LCB. The vertical centers of gravity of the hulls have also been adjusted to get a realistic global GB.

For this reason, the impact of a variation of the COG position is here studied on the example of *'SW'*. Figure 44 and 45 show the variations of pitch RAOs respectively changing LCG and VCG. The variation of LCG is +/-3.2% of hull length and +/-4.8% for VCG. In figure 45, position of G is given compared to waterline.

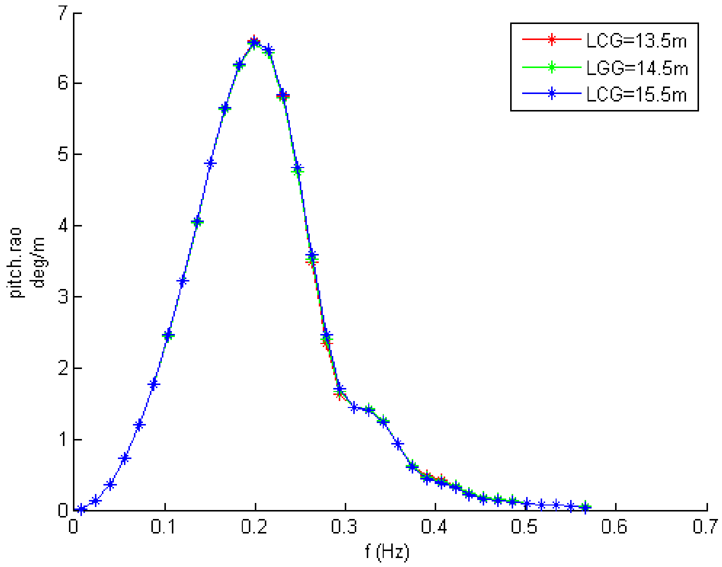

Figure 44. Influence of LCG on 'SW' pitch RAO

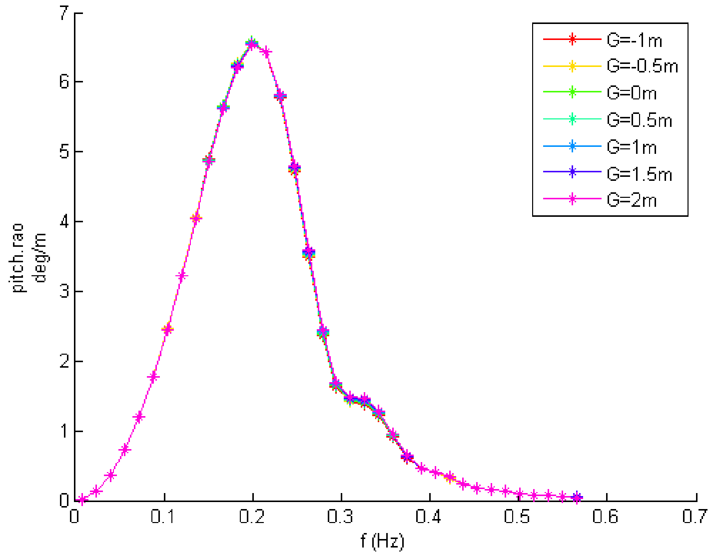

Figure 45. Influence of VCG on 'SW' pitch RAO

9. INFLUENCE OF HULL SHAPE

In this part, the impact of some changes in hull shape on pitch motion is studied.

9.1. Stern Shape

Regarding pitch motion, the shape of bow and stern is critical. Modern sailing hulls tend to have a flat and large stern along with a straight bow. This minimizes the pitch for several reasons. First, it maximizes the waterline length which effect on pitch motion has been described in part 5. Then, large and wide stern increases the wave damping effect which reduces again pitch motion.

On the contrary, older sailing yacht hulls are more narrow and sharp. In that case, the keel is part of the hull and neglected it in the seakeeping calculations might be wrong. Figure 46 shows the example of the *Centurion 32*.

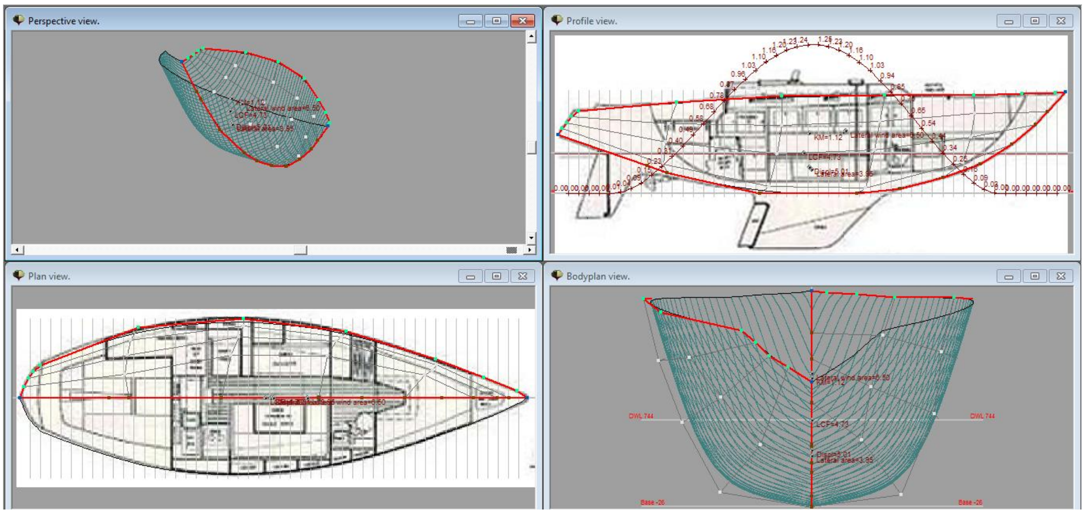

Figure 46. Centurion 32 CAO model

Results in pitch motion computed with *HydroStar* are shown in figure 47 and compared to the other RAOs. The *Centurion 32* has a waterline length of around 8m. Its RAO should be between the one of *J80* and *AME004*. Figure 47 shows that it is the case in term of resonance frequency but that the pitch amplitude is way bigger than expected.

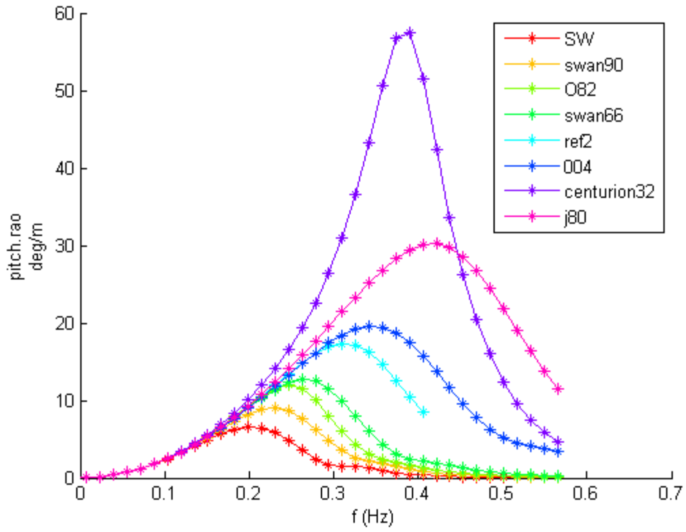

Figure 47. Comparison of Centurion 32 pitch RAO with others

Face to these results, at least two reasons can be invoked: the effect of keel cannot be neglected in that case and/or the bow and stern shape are really critical.

Figure 48 shows the mesh of the underwater part where bow and stern sharp shape can be seen. To see how the stern shape can affect pitch motion, the hull of the *Centurion 32* has been modified only enlarging the stern. Figure 49 shows the modified hull.

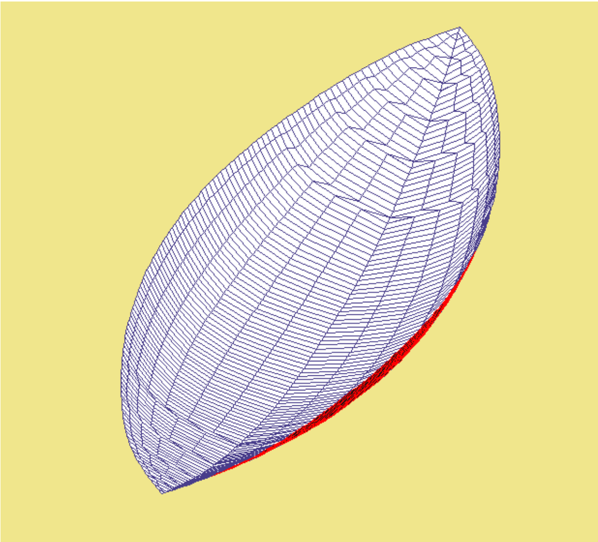

Figure 48. Mesh of the underwater part of the Centurion 32 made with *HydroStar*

Notice the sharp shape of bow and stern

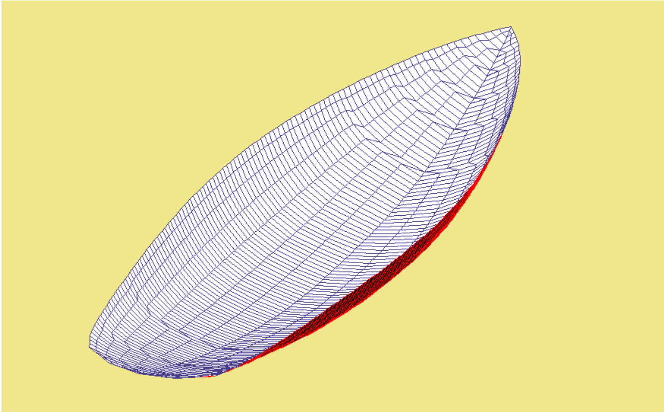

Figure 49. Mesh of the Centurion 32 with enlarged stern

Figure 50 shows a comparison of pitch RAOs between original and modified hull. It shows a big decrease (around 25%) of pitch motion at resonance but results are still quite big. This shows that stern shape is really critical for pitch motion. More investigation and comparison with experiment would be needed to conclude about keel effect.

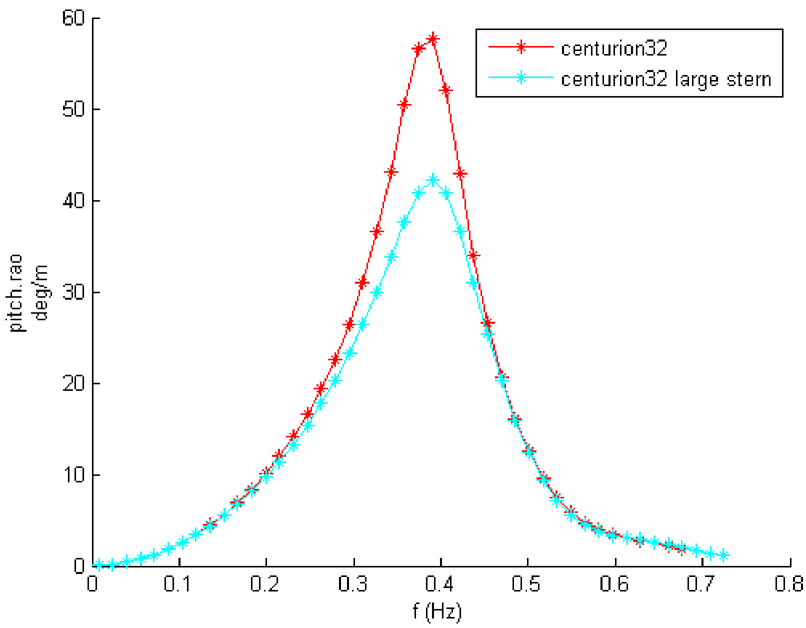

Figure 50. Comparison of pitch RAOs of original Centurion 32 and enlarged stern model

9.2. Beam Draft Ratio

Seeing the results obtained for the *Centurion 32*, it can be thought that it might be due to other differences between modern and old sailing yacht hulls. Apart from bow and stern shape, another big difference between old and modern hulls is that the first ones tend to be more narrow and deep than the second ones.

The idea here was thus to start from a modern hull (the one of the *‘swan66’*) and to modify the beam. The draft was adjusted to keep always the same displacement. Figure 51 shows the transversal view of the original hull and 2 modified hulls (beam increased of 25% and decreased of 25%).

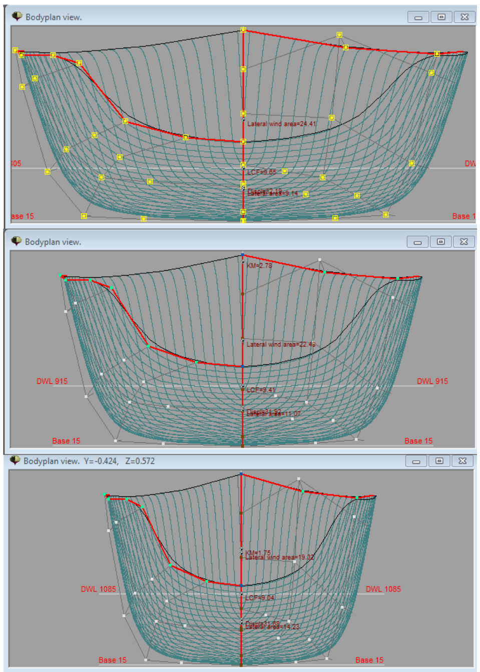

Figure 51. Visualization of beam and draft variation at constant displacement for ‘swan66’

Figure 52 shows the pitch RAOs for these 3 hulls.

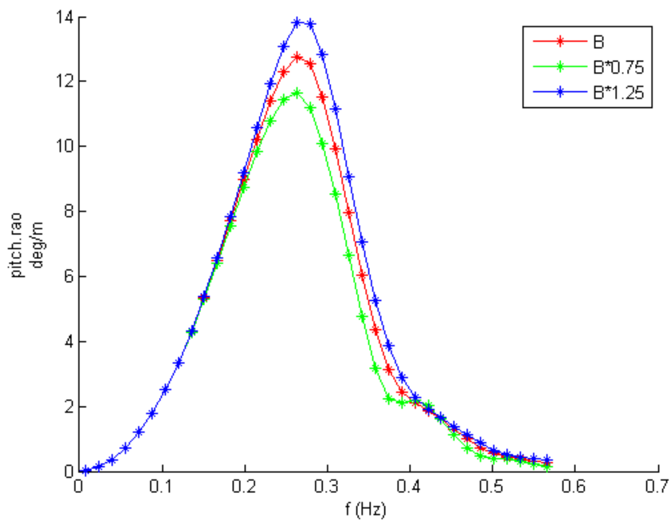

Figure 52. Influence of B/T ratio on ‘swan66’ pitch RAO

It seems that the beam over draft ratio is not so critical concerning pitch motion. Moreover, it looks like deep and narrow hull may decrease pitch motion. It is thus not because of this factor that the *Centurion 32* has such a big pitch amplitude.

9.3. Draft and Displacement

Often the available hydrostatic data is about lightship. Draft and displacement can vary when the crew is on board and all the material loaded. This variation will be bigger with smaller ship. For example with J80, the crew can represent one third of the displacement.

Therefore, a question may be how the pitch motion would be impacted with increasing draft and displacement. Calculations have been performed in the case of the *'swan66'* and results are shown in figure 53 for different drafts (and thus different displacements).

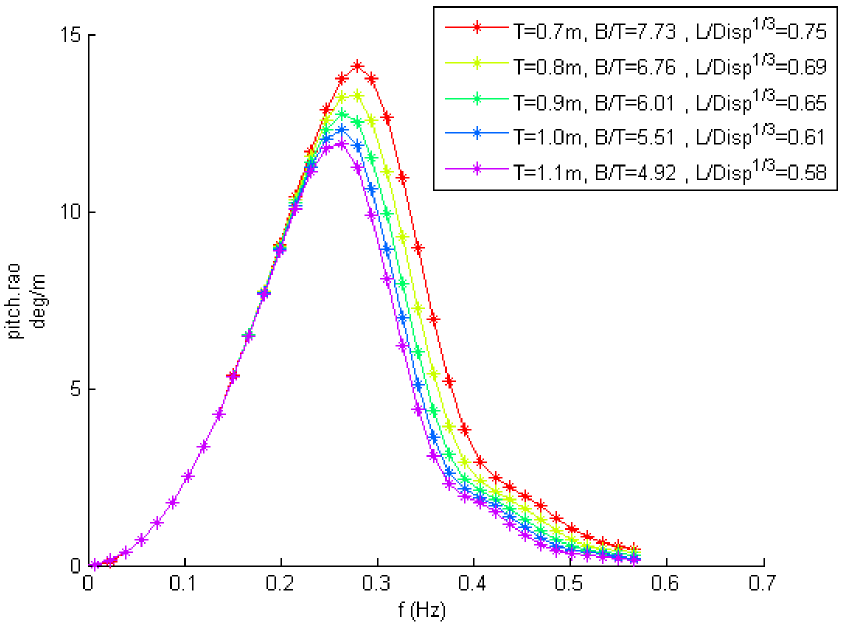

Figure 53. Influence of draft (or displacement) on 'swan66' pitch RAO

Draft and displacement increase look to decrease slightly pitch motion. Note that it modifies also slightly the resonance frequency. The lightship looks thus to be a kind of worst case concerning displacement. Here again, the big draft and displacement of the *Centurion 32* do not justify its big pitch motion obtained with *HydroStar*.

10. REAL SCENARIO

In this part the yacht *Kiboko* is quickly presented. Then, a comparison between pitch RAOs computed with HydroStar and estimated with proposed method is made. Finally, more accurate computations are made with *HydroStar* taking into account more available data.

10.1. Presentation of *Kiboko*

Kiboko is a 94 feet sailing yacht built by *Southern Wind Shipyard* in Cape Town, South Africa in 2010. It is made of sandwich composite (carbon fiber, Kevlar and epoxy resin and Corecell). This boat is being surveyed by *RINA*. Figure 54 shows the real hull when craned to the water along with a view of the CAO model. As show table 7, the value of draft and displacement are quite different between the data given by the shipyard and the data used on the CAO model. This is due to the fact that shipyard displays (very) lightship data. The data used for the calculations were given by *RINA*.

Table 7. *Kiboko* main dimensions

Main dimensions	from SW	CAO model
LOA (m)	28.64	28.64
Lwl (m)	25.96	26.93
B (m)	6.66	6.66
T (m)	4.5	4.7
Lightship displacement (kg)	51500	62795

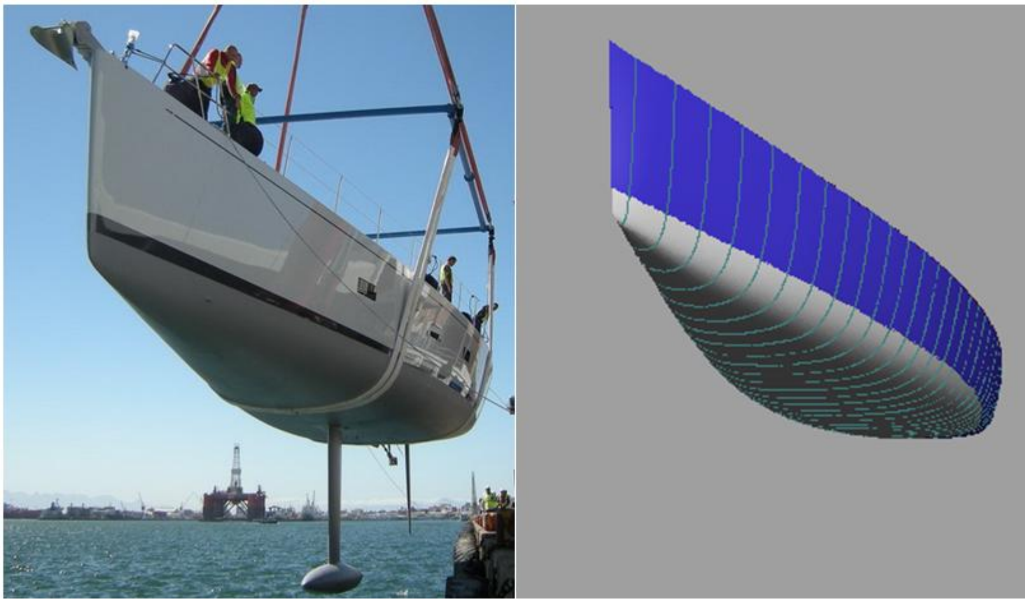

Figure 54. *Kiboko* going at sea (left) and CAO model of the hull (right)

Kiboko is supposed to sail from South Africa to Europe in beginning of 2013. *RINA* hopes to cooperate with *Southern Wind Shipyard* to be able to perform on board measurement during that trip. The idea of the following sub sections is to provide some numerical computations to be later compared with these onboard measurements. Ideally, true wind speed, true wind angle, boat speed should be recorded along with pitch motion and acceleration at mid mast.

10.2. Estimation of Pitch Results with Proposed Method

Kiboko was not part of the small database used to get the approximate method exposed in previous parts. It is the typical kind of hull for which this method is done. It can thus be interesting to try to apply it and compare the estimated results with numerical results.

Kiboko's waterline length used to perform all computations is 26.93 m. Table 8 shows a comparison in term of pitch resonance frequency and maximum pitch amplitude between numerical results and estimated results as exposed in part 5. Here the "default" pitch RAOs are at stake (with pure head sea and no forward speed).

Table 8. Comparison of computed and estimated pitch RAOs

Calculated with *HydroStar*		**Estimated with Lwl**	
pitch resonance frequency (Hz)	maximum pitch (°/m)	pitch resonance frequency (Hz)	maximum pitch (°/m)
0.215	7.4	0.215	7.9

Figure 55 shows the complete comparison of the computed and estimated pitch RAOs.

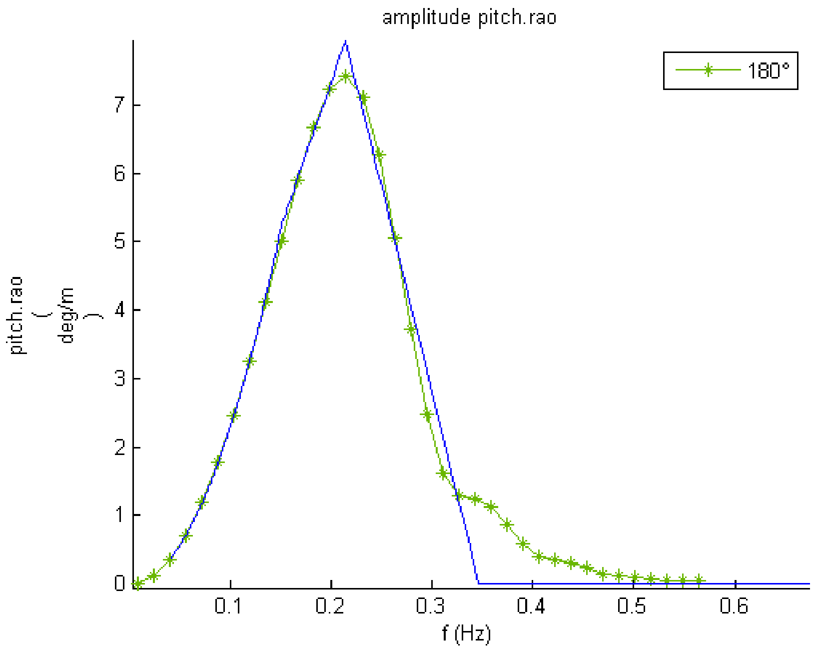

Figure 55. *Kiboko* pitch RAO computed with *HydroStar* (green) and estimated with its waterline length (blue)

To evaluate the accuracy and interest of this estimated RAO, it can be used to get results in irregular sea states. These results can then be compared with the ones obtained in same sea states but with the "real" computed RAO. This comparison is shown in figure 56. Here, the sea states used are with different *Tp* and 2m significant wave height.

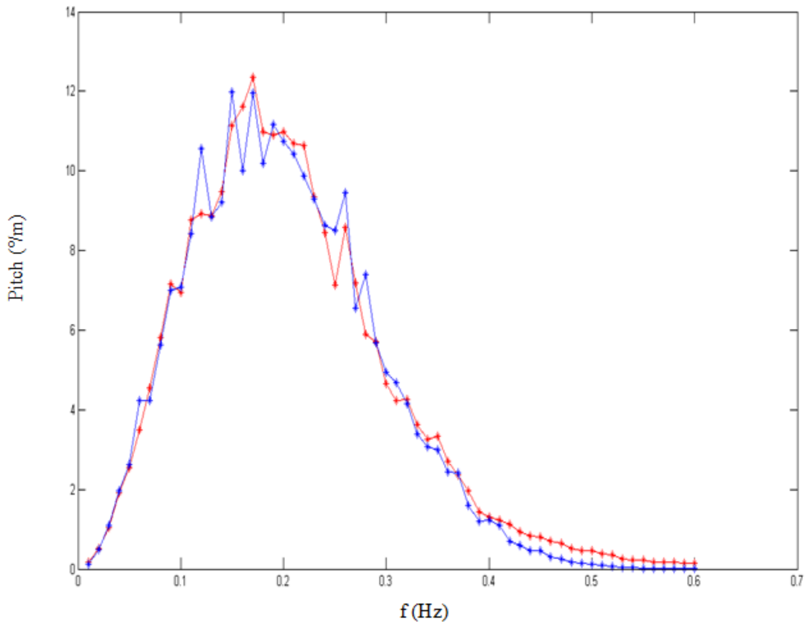

Figure 56. Irregular sea pitching results (Hs=2m, γ=1) obtained by using the RAO computed with *HydroStar* (red) and the estimated RAO (blue)

For both curves, oscillations are due to the random part of irregular sea calculations. In both case, a 3 hours sailing with no forward speed in pure head sea is considered. Getting the estimated results (blue curve) only needs Lwl, Hs, Tp and γ and few seconds of computation time. Very good agreement is shown between numerical and simplified results on this example.

10.3. Wind and Sea Relation

Commonly, the speed of a sailing yacht is given in function of the true wind speed and the true wind angle in a figure called polar diagram. An example of polar diagram is shown in figure 57. This diagram was available for *Kiboko* but cannot be shown here for confidentiality issues.

For a given wind speed, two critical parameters in term of pitch motion can thus be known from this diagram: heading and boat speed. Now, only the waves have to be modeled to run computations.

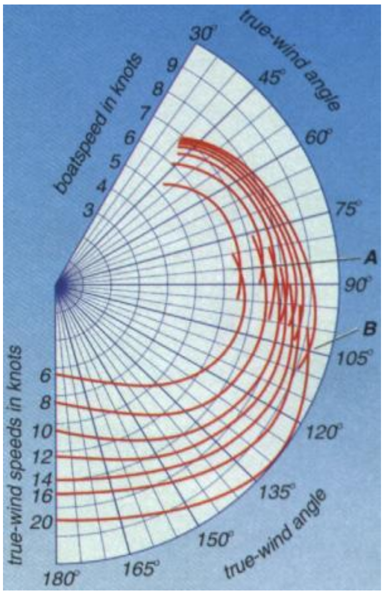

Figure 57. Example of polar diagram

Modeling the sea state just from the wind speed is a very simplified approach as sea state actually depends on other parameters (like wind fetch and duration). In [1], a relation between wind speed and *Hs* and *Tp* is given in northern Atlantic. Relation between wind speed and *Tp* is here used as given in [1] and shown in figure 59. Concerning *Hs*, the curve given in [1] is a bit modified using common data given by Beaufort's scale. Used relation is shown in figure 58.

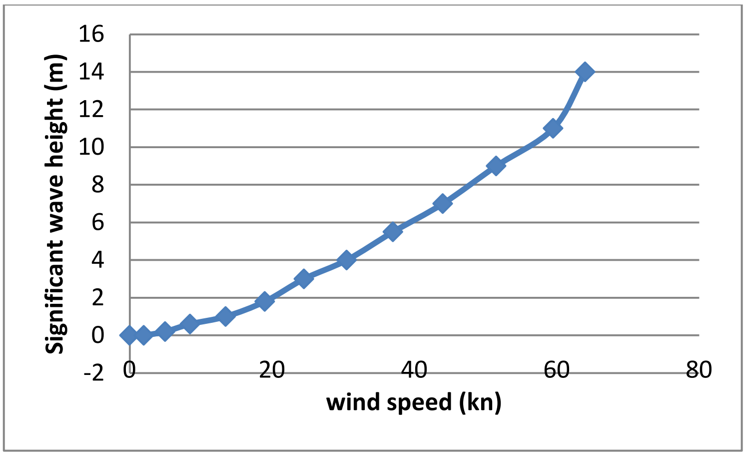

Figure 58. Relation between wind speed and wave height based on [1] and Beaufort's scale

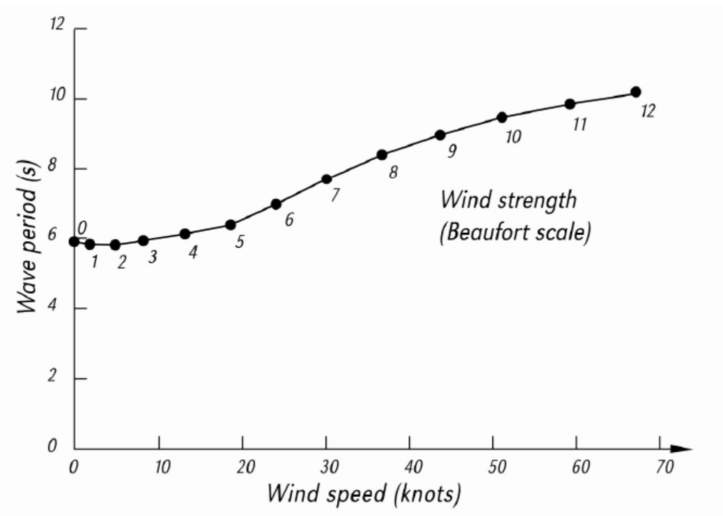

Figure 59. Relation between wind speed and wave period based from [1]

Now, <u>for each wind speed</u> and heading (best upwind heading depends on wind speed):

- The ship velocity is known from polar diagram. Heel angle is neglected.
- The corresponding pitch RAO is computed with *HydroStar*.
- The sea state is modeled from figure 58 and 59 (ɣ=1).
- Maximum response in irregular sea state are computed.

Results are shown in the next subsection for different wind speeds.

10.4. Detailed Results in Sea State

In this sub section, pitch and longitudinal acceleration in the mast results in irregular seas are given as a function of true wind speed. Two cases are performed, going upwind and down wind.

It should be remembered that wind speed variation impacts the ship response in different ways. First, when wind increases, ship speed increases. For each wind speed the ship RAOs are different. Then, stronger winds lead to stronger seas which means bigger waves (so in a way bigger responses) but also bigger periods (which might reduce the response).

Moreover, the heading should also have a strong impact on ship responses. Two cases are analyzed here: head sea/upwind (40 degrees from wind, 140 degrees from waves) and following sea/downwind (135 degrees from wind, 45 degrees from waves). The first case is expected to be close to the worst situation in term of pitching. The impact of heading on responses is also of different kind. First, for each heading, the speeds are different. The RAO also change with heading. Finally, heading strongly affects the encounter frequency so of course ship motions.

Table 9 (resp. 10) shows the results of biggest pitch amplitude and biggest longitudinal acceleration in the mast for a 3 hours trip on an irregular sea state heading upwind at 40° from the wind (resp. heading downwind at 135° from the wind).

Table 9. Pitch and longitudinal acceleration at mid mast results going upwind (40° from wind) for *Kiboko*

TWS (kn)	6	8	10	12	14	16	20	25
Hs (m)	1.2	1.35	1.5	1.65	1.8	2	2.2	3
Tp (s)	5.8	5.9	6	6	6.1	6.3	6.8	7.1
fp (=1/Tp) (Hz)	0.17	0.17	0.17	0.17	0.16	0.16	0.15	0.14
Corresponding encounter period Te (s)	4.33	4.20	4.17	4.09	4.14	4.28	4.68	4.89
Corresponding encounter frequency fe (Hz)	0.23	0.24	0.24	0.24	0.24	0.23	0.21	0.20
Beta/wind (°)	40	40	40	40	40	40	40	40
Beta/wave (°)	140	140	140	140	140	140	140	140
Vs (kn)	7.81	9.43	10.45	11.06	11.46	11.78	12.24	12.71
Vs (m/s)	4.02	4.85	5.38	5.69	5.90	6.06	6.30	6.54
Pitch in irregular waves (°)	7.9	8.7	9.1	9.7	10.5	11.6	11.9	16.3
AccXmast in irregular waves (m/s²)	11.5	13.3	15.4	17.7	18.6	20.7	20.7	27.5

Table 10. Pitch and longitudinal acceleration at mid mast results going upwind (135° from wind) for *Kiboko*

TWS (kn)	6	8	10	12	14	16	20	25
Hs (m)	1.2	1.35	1.5	1.65	1.8	2	2.2	3
Tp (s)	5.8	5.9	6	6	6.1	6.3	6.8	7.1
fp (=1/Tp) (Hz)	0.17	0.17	0.17	0.17	0.16	0.16	0.15	0.14
Corresponding encounter period Te (s)	9.32	10.79	11.82	12.88	13.95	14.94	17.06	21.04
Corresponding encounter frequency fe (Hz)	0.11	0.09	0.08	0.08	0.07	0.07	0.06	0.05
Beta/wind (°)	135	135	135	135	135	135	135	135
Beta/wave (°)	45	45	45	45	45	45	45	45
Vs (kn)	9.41	11.47	12.68	13.76	14.73	15.64	17.55	20.19
Vs (m/s)	4.84	5.90	6.52	7.08	7.58	8.05	9.03	10.39
Pitch in irregular waves (°)	3.7	3.8	4.6	5.0	6.1	6.6	7.1	11.5
AccXmast in irregular waves (m/s^2)	0.6	0.5	0.5	0.5	0.6	0.7	1.0	2.4

As expected, pitch motion and acceleration in the mast are much worst going upwind than downwind. This confirms that studying head sea case for pitch motion was relevant. For example, a wind of 25 knots downwind leads to the same pitch downwind than 16 knots upwind even if going much faster downwind. Moreover, it leads to much smaller acceleration in the mast even if same pitch amplitude. Note that the simplified methods proposed in part 5 and 6 do not apply here with forward speeds, mostly for accelerations.

Figures 60 and 61 show respectively biggest pitch response and biggest longitudinal acceleration in the mast in function of wind speed for a 3 hours trip in irregular sea heading 40° from wind. Motions tend to get worst and worst with wind speed. More calculations for bigger wind may be interesting even if it might start to be out of model range.

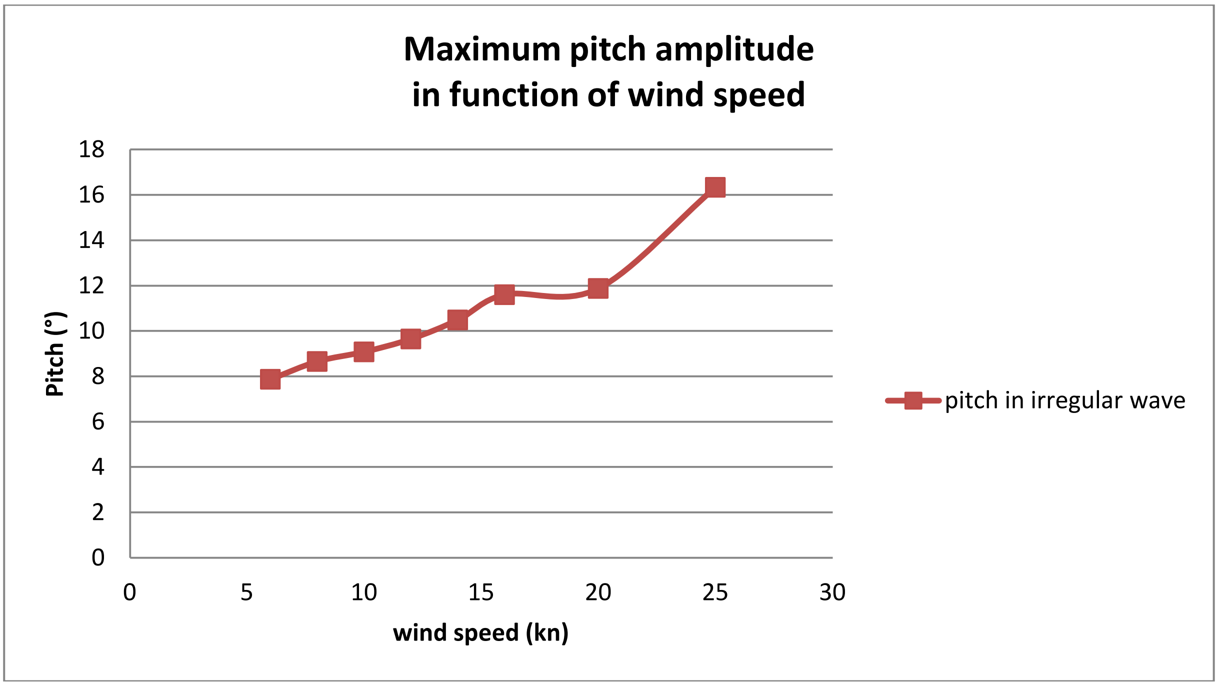

Figure 60. Mean maximum forecast pitch for *Kiboko* sailing 3 hours in function of wind speed

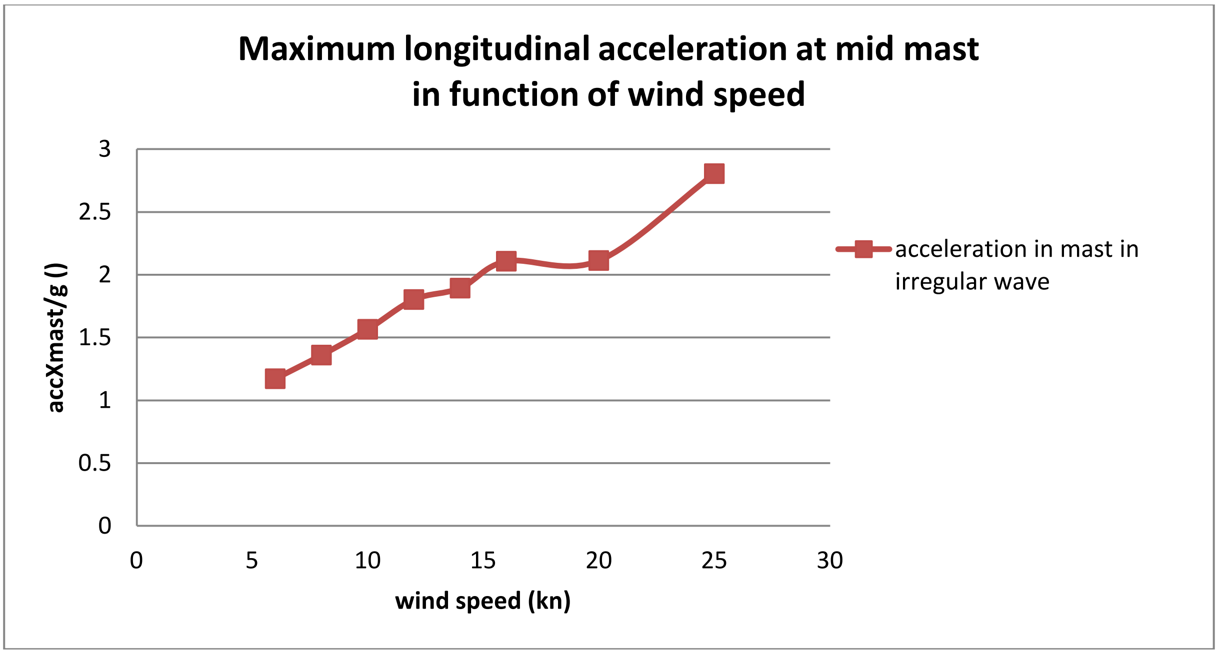

Figure 61. Mean maximum longitudinal acceleration at mid mast for *Kiboko* sailing 3 hours in function of wind speed

11. CONCLUSION

In this work, the pitching behavior of a small set of hulls has been studied with *HydroStar* software. A very quick and simple formulation has been proposed to estimate the pitch RAO of a modern sailing hull in head sea, with no forward speed. This formulation is only based on hull waterline length. A rough formulation to estimate the order of magnitude of the acceleration in the mast has also been exposed. These estimations are irrelevant with forward speed.

Then, a state-of-the art process has been set to get seakeeping results in irregular seas. It has been successfully compared with real on board measurement. The influence of sea state parameters on pitch motion has been studied, leading to the concept of irregular sea RAO. It seems to show that motion in irregular see could be estimate by multiplying the motions in regular sea by a factor depending on the time spent at sea.

Moreover, the influence of different parameters on pitch motion has been investigated through examples. Key parameters to the pitching behavior are (at least): waterline length, pitch radius of gyration, stern shape, bow shape, heading and forward speed.

Finally, a test case has been carried out on *Kiboko*. The proposed method to estimate the pitching behavior in head sea with no forward speed works well on this yacht. In addition, a forecast of pitch amplitude and longitudinal acceleration in the mast in function of wind speed has been set, with hope to compare it with real onboard measurements in the next months.

As this work was a preliminary study, a lot of work could be done to improve it. Some suggestions can be made already:

- Improve the simplified formulation proposed by taking into account the effect of other important parameters highlighted before.
- Build a much bigger database, get results and perform a regression using these key parameters to estimate better the pitching behavior.
- Keep comparing results with incoming on board measurements on *Kiboko*, *J80*…
- Investigate the relevancy of the results out of the range of the model (e.g. in breaking waves).

12. ACKNOWLEDGEMENTS

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APPENDIX 1

- ‘SW” stands for the *SW 100 RS* ship from *Southern Wind* shipyard. CAO hull was provided by *RINA*. Commercial information can be found on southern wind website [7].
- ‘swan 90’ stands for the boat of the same name by *Nautor’s Swan*. Commercial information can be found on company website [8]. CAO model was made by the author.
- ‘oyster 82’ stands for the yacht of the same name by *Oyster Marine*. Commercial information is available on company website [9]. CAO model was made by the author.
- ‘swan 66’ stands for the boat of the same name by *Nautor’s Swan*. Commercial information can be found on company website [8]. CAO model was made by the author.
- ‘ref2’ is a hull designed by the author only based on the main dimensions of the hull used in [1]. No plan was used to design it.
- ‘AME004’ is an IMS type yacht based on the Delft Systematic Yacht Hull Series II yacht form. It was designed to copy the reference hull used in [2]. It was given by *RINA*.
- ‘J80’ stands for the famous boat of the same name. It is the reference 8m sailing boat. The J80 is one of Europe's and North America's best selling sportsboats. More information can be found on [10]. CAO model was given by *RINA*.
- ‘Centurion 32’ stands for the boat of the same name by *Wauqiez*. CAO model was made by the author. All information used can be found on [11].
- ‘Kiboko” stands for the *SW 94* ship from *Southern Wind* shipyard. CAO hull was provided by *RINA*. Commercial information can be found on southern wind website [7]. Confidential information was also given by *RINA* about this boat.