A SIMPLIFIED METHOD TO ASSESS ACCELERATION LOADS ON SAILING YACHT MASTS

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The behaviour of sailing boats in open sea is strictly related to their hydro and aerodynamic performances and to the wide range of loads acting on the hull and rigging system. Their evaluation could be done only by a careful seakeeping analysis with particular attention to the acceleration loads caused by hull motions which can create severe problems to mast and rigging up to extreme consequences such as dismasting. The main reasons of dismasting are related both to human errors and to the lack of load knowledge; as a matter of fact Classification Societies' Rules are quite poor about this subject and the structural design if often committed to the designer experience. The aim of this work is to investigate on the hull dynamic responses which mainly influence the mast and rigging loads with particular attention focused on the pitching behaviour of the vessel. With this goal in mind the seakeeping behaviour of a number of sailing yachts, different each other in sizes and typology, has been investigated. Despite the small size of the database, the achieved results allowed to formulate a preliminary simplified method to estimate the pitch Ratio Amplitude Operator (RAO), based only on the boat length. From the pitch RAO knowledge a very rough and quick formulation to evaluate the longitudinal acceleration in the mast centre of gravity has been obtained.

NOMENCLATURE

a	Amplitude of wave (m)
B	Breadth (m)
B_{wl}	Waterline breadth (m)
β	Angle of heading (degrees)
γ	Peakness factor
D	Draught (m)
Δ	Displacement (Kg)
ε	Wave slop (m)
f	Frequency (Hz)
g	Gravity acceleration (m/s^2)
H	Wave height (m)
k_{yy}	Gyration radius (m)
λ	Wavelength (m)
λ_0	Wavelength for which the RAO is equal to 0,05 in terms of pitch/wave slope(m)
λ_1	Wavelength for which the RAO is equal to 0,95 in terms of pitch/wave slope(m)
L_{ao}	Overall length (m)
L_{wl}	Waterline length (m)
p_{max}	Pitch RAO maximum
RAO	Ratio Amplitude Operator
S	Spectrum (m^2/s)
T	Period (s)
t	Time (s)
U	Forward speed (m/s^2)
φ	Phase (degrees)
ω	Wave pulsation (rad/s)

1 INTRODUCTION

With regard to sailing yachts, dismasting is considered an impressive and extreme event, very dangerous for crew and for the vessel. Nowadays some Classification Societies have a section in their Rules specifically dedicated to mast and rigging scantling [1] - [6]. In particular, the Italian Classification Society RINA, recently published a draft of its new Rules in which a specific section for sailing yacht design has been introduced [7]. Nevertheless the last word about mast and rigging design is often left to designers and mast builders and the first step of this activity should be the full understanding of acting loads. Two kinds of loads can be individuated: aerodynamic loads due to wind action on sails and inertial loads due to the yacht motion in waves; a complete review of all loads to be considered in yacht design can be found in [8]. In this paper attention has been focused on sea loads and, after a first investigation, performed also on references made available in literature, such as [9], [10], [11] and [12], the main hull response leading to important acceleration loads on mast has been individuated on pitching motion.

A comprehensive study on the pitching behaviour of sailing yachts at sea has then been carried out by means of the well known seakeeping software *HydroStar* [13]. This is a linear potential flow solver using panel methods in frequency domain and developed by Bureau Veritas. When nothing is explicitly specified, RAO calculations are carried out with no heel, no forward speed and in pure head sea.

The analysis has been carried out on a database of seven modern sailing yacht hulls of different lengths and typology, from 8 to 30 meters in length.. Basic hull descriptions have been derived from commercial leaflet or shipyard web site, where only few information are available. In most cases, main dimensions (such as length, beam, displacement, ballast weight) and only top and longitudinal views are given. A synthesis of the considered boats is presented in Table 1. Starting from these information CAO models have been created using the open software *FreeShip* [14]. Only the canoe hull bodies are modelled, assuming that with regard to pitch motion, the keel effect is negligible.

Table 1: Main dimensions of the seven hulls considered.

Name	L_{OA}	L_{wl}	B	D	Δ	Ballast Mass	k_{yy}
	(m)	(m)	(m)	(m)	(Kg)	(Kg)	(m)
Southern Wind (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
SY 50 (Ref 2)	14.5	12.8	4.3	0.66	12877	4507	3.63
AME004	11.3	10.3	3.1	0.44	5381	1883	2.79
J80	8.0	7.0	2.5	0.34	1825	635	2.11

2 IMPORTANT YACHT HULL PARAMETERS

The influence on pitch RAO of different hull parameters has been deeply analysed in this study. Some of them have been proven to have a significant impact on the pitching behaviour of a sailing hull at sea, whereas others have been found to have a negligible impact. The most critical parameters are listed and discussed in the following subsections.

Before any other activity a comparative analysis has been carried out in order to set up the various *HydroStar* parameters. The study has been performed on the yacht called “AME004” on which huge real scale measurements of ship motions have been performed at sea and published in [10].

The AME004 hull has been modelled by *FreeShip* software and the results obtained by *HydroStar* calculations have then been compared with experimental ones. The comparison of pitch RAO results are plotted in Figure 1 and they show a good agreement.

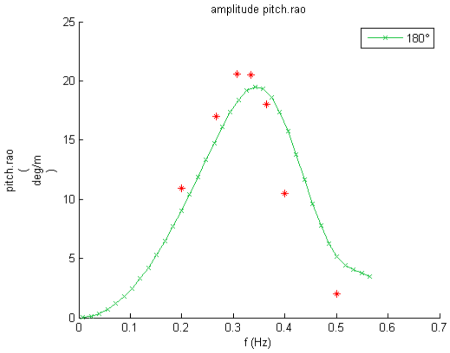

Figure 1: Pitch RAO from *HydroStar* compared with experimental results of [10] (red dots).

2.1 WATERLINE LENGTH L_{wl}

The seven hulls collected in our database are different in sizes but quite similar in shape. Therefore, the reference parameter assumed in this study is the waterline length L_{wl}. By using potential methods, only the underwater parts of the hulls are taken into account. The seven pitch RAOs obtained by *HydroStar* calculations are displayed in Figure 2. The waterline length is obviously the most critical parameter driving pitch motion.

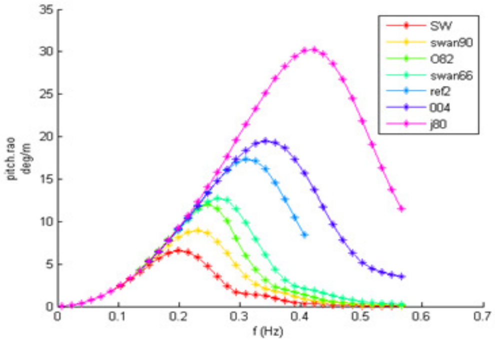

Figure 2: Pitch RAOs of the seven yachts obtained by *HydroStar* calculations.

2.2 PITCH GYRATION RADIUS

Typically, for modern sailing boats, the pitch radius of gyration k_{yy} is in the range [0.25 L_{wl} - 0.35 L_{wl}]. For the considered boats, they have been found to be between 0.27 L_{wl} and 0.30 L_{wl}. As a consequence, the impact of pitch gyration radius varying in this range has been studied.

It can be expected that gyration radius will change the maximum value of the pitch RAO and the value of the resonance frequency as well. 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 related to the stiffness over inertia ratio). On the other hand, the peak at resonance should be bigger.

Let us define some value that will describe the simplified RAO:

- λ_1: the wave length (m) from which the boat starts to simply follow the wave and f_1 the corresponding wave frequency. It can be defined as the wave length for which the RAO is equal to 0.95 in terms of pitch/wave slope;
- λ_0: the wave length (m) up to which the boat does not respond to the wave and f_0 the corresponding wave frequency. It can be defined as the wave length for which the RAO is equal to 0.05 in terms of pitch/wave slope.

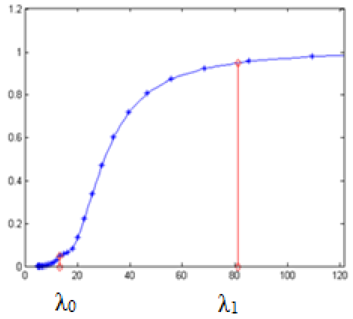

Figure 3 : three regions of interest on ‘SW’ pitch RAO plotted as pitch/wave slope against wave length.

Figure 4 shows the pitch RAOs of the ‘Swan 66’ for different pitch gyration radius. The resonance does not seem to change significantly in this range of kyy.

Figure 5 shows the same results but plotting the RAOs in term of pitch over wave slope as a function of wave length. It can be noticed that the motion in the “range of interest” between λ_0 and λ_1 is quite sensitive to k_{yy}. On the other hand, out of this range, results are quite similar. The estimation of the RAO in the range λ_0 - λ_1 might thus be refined in the future, using the value of k_{yy} in some way.

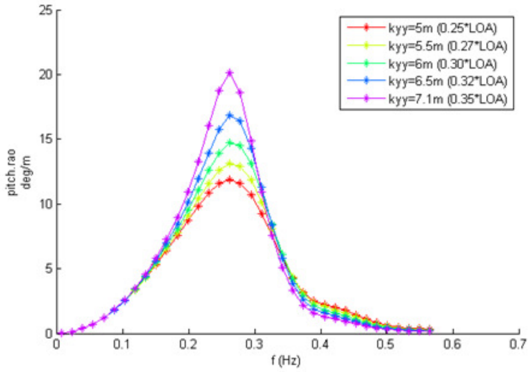

Figure 4: Influence of the pitch gyration radius k_{yy} on ‘Swan 66’ pitch RAO.

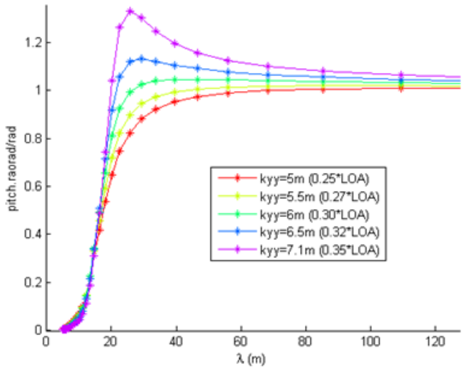

Figure 5: Influence of the pitch gyration radius k_{yy} on ‘Swan 66’ pitch RAO plotted as a function of wavelength.

2.3 FORWARD SPEED

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

Anyway, the effect of forward speed is double:

- first it changes the equations to be solved by changing the boundary conditions of the potential problem;
- secondly it determines the encounter frequency.
-

Indeed, if the wave has a frequency "f" the boat “experiences” and responds at the frequency "f_e"

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

where:

- β is the heading angle (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 yacht ‘SW’ is shown in Figures 6 and 7 respectively for pitch RAO and longitudinal acceleration at middle height of the mast.

The forward speed effect on pitch is quite 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 yacht has to make the same pitch but quicker at 10 knots rather than at 0 knot.

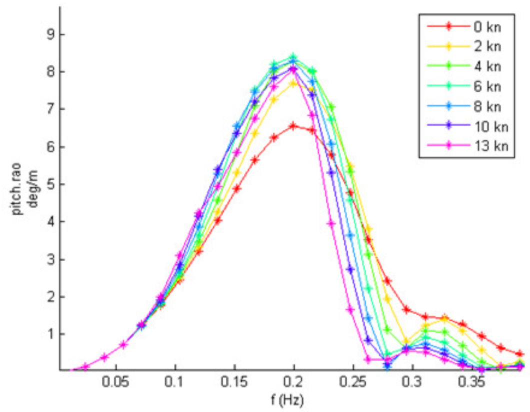

Figure 6: Influence of forward speed on ‘SW’ pitch RAO.

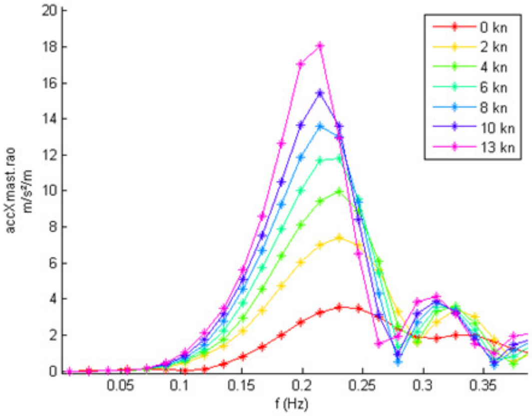

Figure 7: Influence of forward speed on ‘SW’ mast acceleration RAO.

2.4 HEADING

Till now, only motion in pure head sea (180° heading) has been considered. This approach is justified by the fact that the maximum pitch happens when going up sea (which is generally also upwind). The pure head sea is not necessarily the worst case in term of pitching, as shown in Figure 8.

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

For a sake of simplicity, in the following pitch motion is thus studied in pure head sea by default.

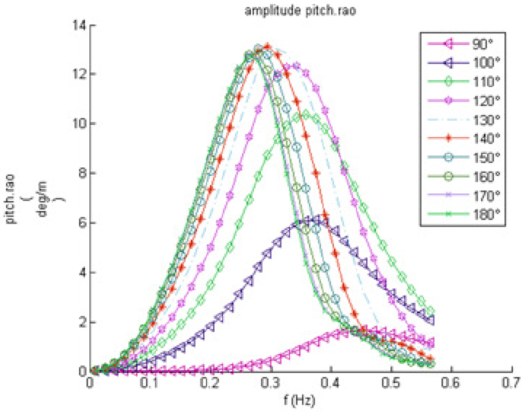

Figure 8: Influence of heading on ‘Swan 66’ pitch RAO.

2.5 STERN SHAPE

With regard to 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 decreases pitch motion. Then, large and wide stern increases the wave damping effect which, again, reduces pitch motion. On the contrary, older sailing yacht hulls are narrower and sharper. In that case, the keel is part of the hull and to neglect it in the seakeeping calculations may be wrong.

Figure 10 shows the example of the Centurion 32 with original hull and enlarged stern.

Predicted pitch motion is surprisingly big but, as expected, results to be reduced by assuming an enlarged stern.

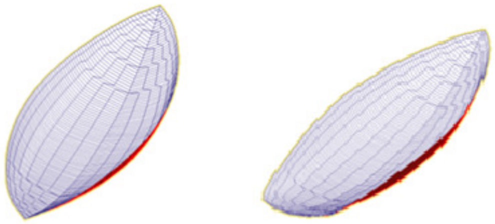

Figure 9: Mesh of the original Centurion 32 (left) and with enlarged stern (right)

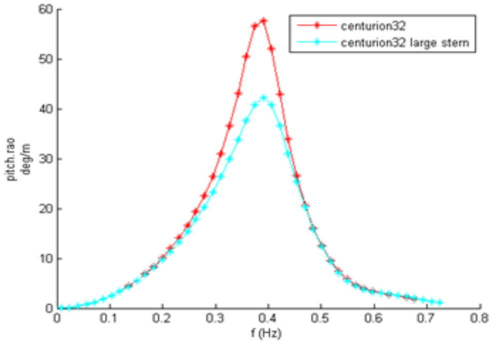

Figure 10: Comparison of pitch RAOs of original Centurion 32 and enlarged stern model.

Among the tested parameters, the following ones has proven to be of great influence on pitch motion:
- waterline length;
- pitch gyration radius;
- forward speed;
- heading;
- stern shape.

Other parameters have been investigated without showing important impact on pitch motion, such as:
- heel angle;
- keel shape;
- water depth;
- centre of gravity position;
- beam-draft ratio;
- draft-displacement ratio.

3 SIMPLIFIED METHOD FOR QUICK PITCH MOTION AND ACCELERATION ASSESSMENT

In this section, a very simple method is proposed to quickly estimate pitch motion and induced acceleration on the mast. The driving idea is to provide a fast method to assess these values by simple formulas, without using any software. From considerations given in part 2, the method herein proposed is only based on yacht waterline length. In addition it can be valid only in case of head sea and with no forward speed.

3.1 SIMPLIFIED PITCH RAO

The starting point of this method is to consider the pitch RAO plotted in a different way. Usually, the pitch amplitude for a 1 m wave is plotted against wave frequency or pulsation. In this approach, the pitch amplitude divided by wave slope (or steepness) has been plotted versus the wave length. Indeed, linear wave theory in infinite water gives a unique relation between wave period and wave length, through the dispersion equation:

$$\lambda = 1.56\ T^2 = 1.56/f^2$$

Then, the wave slope is given by:

$$\varepsilon = \frac{2\pi}{\lambda} * a = \frac{2\pi}{\lambda} * 1m$$

It's clear that for long waves, the boat just follows the wave and its maximum pitch is equal to the wave slope. On the other hand, for very short waves, the boat almost does not respond.

Now, let us define some values that will describe the simplified RAO:

- λ_{res}: the resonance wave length (m) and f_{res} the pitch resonance frequency (Hz);
- p_{max}: the pitch for one meter wave at resonance frequency (°/m).

The regression based on the yacht waterline highlights a linear correlation between L_{wl} and both λ_{res} and λ_0. Then, the approximated pitch RAO is obtained by:

- the wave slope for $f < f_1$;
- 0 for $f > f_0$;
- simple triangulation using the point (f_{res}, p_{max}) for $f_0 < f < f_1$.

A comparison between pitch values calculated by *HydroStar* software and determined by the present simplified method (based on L_{wl}) has been carried out; the assumed case study is the sailing yacht "Kiboko" built by "Southern Wind Shipyard" and not belonging to the seven yachts database.

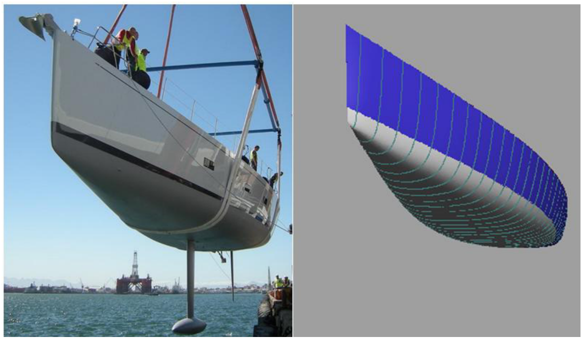

Figure 11: "Kiboko" sailing yacht during launching and the corresponding CAO model prepared by FreeShip.

Results can be seen in the following Figure 12.

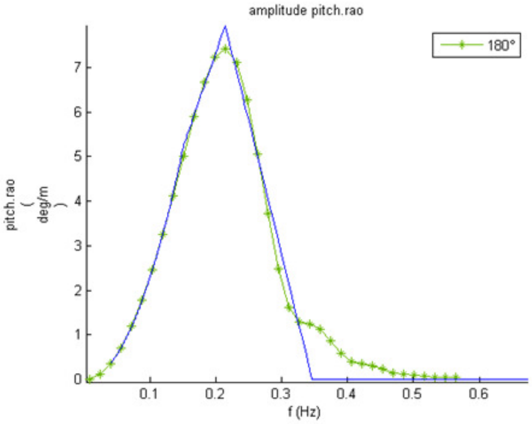

Figure 12: "Kiboko" pitch RAO computed by *HydroStar* (green) and estimated by her waterline length (blue).

Table 2: 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

3.2 EXTENSION TO A ROUGH MAST ACCELERATION ESTIMATION

A very important capability of *HydroStar* software is to provide accelerations at any point of the vessel, taking into account different motion coupling. Nevertheless, as the authors' aim is, it could be of interest to assess roughly and quickly the mast acceleration without the necessity of using any software. The idea here is to assume that the worst case, for what mast acceleration are concerned, occurs at pitch resonance. Moreover, let us assume that the total longitudinal acceleration can be approximated by the pitch acceleration only.
Then, starting from the results exposed in part 3.1, the estimation of the mast acceleration can be derived in the following way:

- evaluate pitch resonance frequency and pulsation ($\omega_{res)}$ and maximum of the pitch RAO (p_{max});
- evaluate the lever arm. For example in the mid mast, it can be roughly estimated as $\frac{(1.5*LOA)}{2}$;
- evaluate peak acceleration value (for 1m wave amplitude) by "deriving" twice the motion value and multiplying by lever arm:

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

Table 3 shows the estimated maximum acceleration for 1m wave compared to the one computed by *HydroStar* software. The estimation is made making reference only to L_{OA} and L_{wl}. Here, these values are obtained from the yachts used to build the model.

Table 3: Comparison of computed and estimated longitudinal accelerations at mid mast.

Name	accXmast max computed	accXmast max estimated	Ratio
	$m/s^2/m$	$m/s^2/m$	
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

4 MOTION IN IRREGULAR SEA STATES

4.1 THEOEITICAL FORMULATION

Previous results were obtained in regular or harmonic waves while, as a matter of fact, sea free surface is irregular. In the linear theory approach the sea surface elevation is decomposed in a sum of regular waves. The sea surface profile can be written, making reference to a fixed axis system, as:

$$\eta(t) = \sum_{i=1}^{\omega} \left(a_i \cos(2\pi f_i t + \varphi_i)\right)$$

The dependence from 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:

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

The RAO used in this procedure is the one computed for the heading of interest.
A fundamental 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.

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

With $\sigma = 0.07$ if $f < f_p$ and $\sigma = 0.09$ if $f > f_p$
Such a spectrum is completely defined by three parameters:

- the significant wave height H_s. 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 H_s;
- the peak period $T_p = 1/f_p$. It is the period corresponding to the peak of the spectrum;
- the "peakness" factor γ. It describes the width of the peak or how the peak is spread over frequencies. Typical values of γ are 1 (fully developed sea) and 3.3 (wind sea).

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

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

From the spectrum, the time series can be reconstructed by:

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

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”. To a real wave frequency *f* it corresponds an encounter frequency f_e :

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

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

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

In that case, the RAO to be used is that computed with the heading of interest and at the forward speed of interest, computed in this work by *HydroStar* software.

4.2 COMPARISON WITH EXPERIMENTAL RESULTS

Unfortunately a large amount of experimental data to be compared with this model doesn't exist. In [11], real scale on board measurements of pitch motion were performed. The yacht is a J80 sailing yacht. From personal communication with the authors of this paper, some information about the test conditions have been obtained:

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

Experimental results are given as a plot of the pitch time series over 35 seconds (see Figure 13).

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

- in pure front waves (heading of 180 degrees);
- with a speed of 5 knots;
- in a sea state of H_s = 0.3 m, T_p = 2.251 s (which corresponds to encounter period of 1.3 s) and with γ = 3.3 (as the basin is closed, the sea was probably not fully developed);
- no heel angle.

Comparison of time series over 35 s can be seen in Figure 13.

This comparison shows very good agreement in terms 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 13 will never superimpose but what matters is the significant height and period of the response.

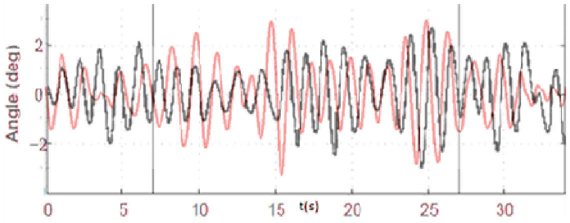

Figure 13: Comparison of pitch time series measured in [11] (in black) and computed (H_s = 0.3 m, T_p = 2.25s and γ = 3.3, in red).

However, the longer a yacht stays on a given sea state, the more likely it is to meet a wave bigger than the average wave. A value that can be recorded is the maximum response staying a given time in 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”.

4.3 IRREGULAR SEA STATE RAO

As previously explained, the maximum value of yacht response at sea during a given duration can be recorded. A typical duration for a sea state to be considered constant is 3 hours. This duration is used in the following.

Some computations showed that the influence of the peak enhancement factor value almost does not impact on the values of this maximum. On the other hand, the significant wave height and the peak period/frequency impact a lot on this value. Figure 14 shows, for a given peak frequency, the influence of the significant wave height on the maximum pitch response.

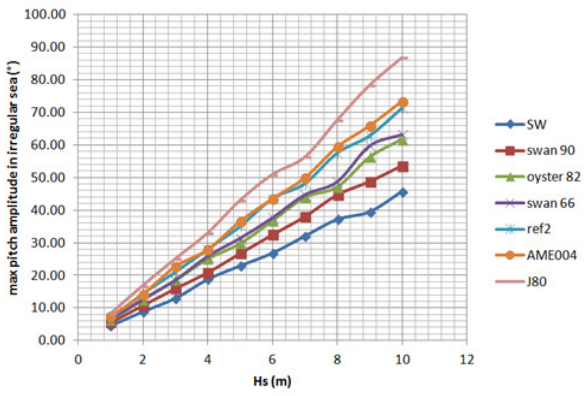

Figure 14: Influence of significant wave height on pitch motion.

As a linear theory has been used, the maximum responses linearly depend on the (significant) wave height. The wave height can be considered to be $H_s = 2$m (i.e. 1m amplitude). Then, as for regular waves, the results in term of maximum response in an irregular sea state can be plotted as a function of the peak frequency only. It is the definition of a RAO, but here in irregular sea state. Figure 15 and 16 show an example for the pitch and the acceleration at mid-mast.

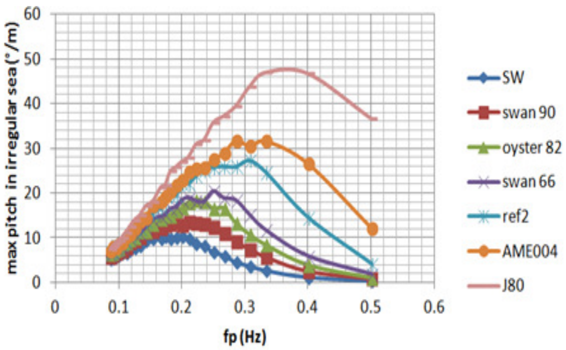

Figure 15: "Irregular pitch RAOs". Maximum pitch for a 3 hours sailing in irregular head sea, with $H_s = 2$ m, $\gamma = 1$ and no forward speed.

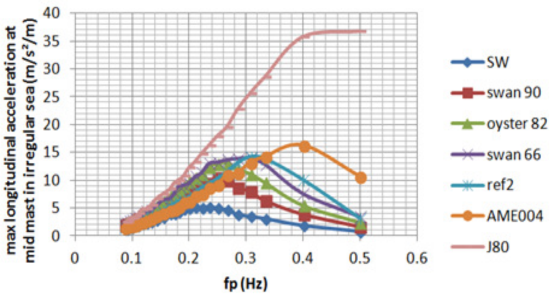

Figure 16: "RAOs of irregular sea acceleration in the mast centre of gravity". Maximum longitudinal acceleration at mid mast for a 3 hours sailing in irregular head sea, with $H_s = 2$ m, $\gamma = 1$ and no forward speed.

The results obtained for irregular sea RAOs are bigger than for RAOs in regular sea; this can be explained by the fact that in a sea state of 2 m significant wave height (1 m amplitude), the boat can experience to meet waves of bigger amplitude.

Using this representation, the irregular pitch RAO of Kiboko yacht can be plotted using both the regular RAO computed by *HydroStar* and the estimated RAO obtained by the proposed method. This is depicted in Figure 17. The oscillations are due to the random part of the irregular wave generation.

This diagram shows very good agreement in terms of real pitch motion in irregular sea. The results using computed and estimated RAOs are really similar. It can be again recalled that the blue curve is obtained without using any hydrodynamic software.

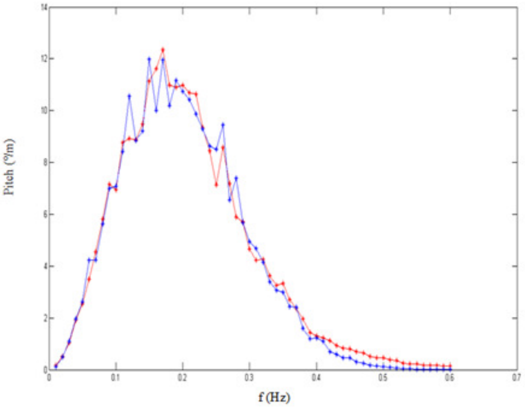

Figure 17: Irregular sea pitching results (H_s=1m, γ=1) obtained by using the RAO computed by *HydroStar* (in red) and the RAO estimated by the presented procedure (in blue)

5 CONCLUSIONS

The main objective of this work was to investigate on maximum accelerations acting on the mast and rigging system of yachts when sailing in severe sea states. In the preliminary phase of the study it has been verified that the parameter which mainly affects mast accelerations is represented by the pitch response of the vessel. In the second phase the influence of different variables on pitch motion has been deeply investigated. Key parameters of the pitching behaviour have been individuated to be: waterline length, pitch radius of gyration, stern shape, heading and forward speed. In order to have a wide and reliable set of results a number of sailing yachts has been collected in a data base ranging from 8 to 31 meters in length. The described calculations have then been carried out on all the yachts of the database. For seakeeping analyses the well known *HydroStar* software by Bureau Veritas, has been utilised.

In the third phase of this work, starting from the gathered seakeeping results, 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 the hull waterline length and it represents a first, rough approach to estimate the order of magnitude of the acceleration in the mast. These estimations are irrelevant with forward speed.

In the final phase, 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 measurements performed on the sailing yacht "Kiboko". In case of no forward speed, pitch motion RAO in irregular sea seems to satisfactorily match those obtained by the proposed simplified method.

This work is to be considered as a preliminary study of mast and rigging response to yacht motions at sea and many further improvements appeared to be very interesting to the authors during the development of the performed investigations. In the following some possible hints are presented:

- improve the simplified formulation proposed by taking into account the effect of other important parameters highlighted before, such as forward speed;
- build a much bigger database, get results and perform a regressions using these key parameters to better estimate the pitching behaviour;
- keep comparing results with incoming on board measurements on Kiboko and other sailing yachts;
- investigate the relevance of results out of the range of the linear model (e.g. in breaking waves).

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