High-speed craft dynamics in waves: challenges and opportunities related to the current safety philosophy

Anders Rosén, *KTH Royal Institute of Technology, Stockholm, Sweden*, aro@kth.se
Ermina Begovic, *University of Naples "Federico II", Naples, Italy*, begovic@unina.it
Mikael Razola, *SSPA, Stockholm, Sweden*, mikael.razola@sspa.se
Karl Garme, *KTH Royal Institute of Technology, Stockholm, Sweden*, garme@kth.se

ABSTRACT

This paper considers the assessment of vertical accelerations of high speed planing craft in waves as the principal element for the risk management approach, i.e. formulation and application of operational limitations and operational guidance. Semi-empirical methods used by classification societies for vertical acceleration assessment are scrutinized. Insights from model experiments performed at the University of Naples "Federico II" (UNINA) and simulations performed at the Royal Institute of Technology (KTH) are presented. Deficiencies of the prevailing semi-empirical methods, and challenges and opportunities with a combined experimental-numerical approach, are discussed in perspective of the IMO high-speed craft safety philosophy.

Keywords: *high-speed craft, impact accelerations, experiments, simulations, safety philosophy, IMO HSC Code, class rules*

1. INTRODUCTION

High-speed craft operating in planing modes are subject to numerous stability related hazards, e.g.: reduction of transverse stability with increasing speed; chine tripping; chine walking; porpoising; bow diving; and directional instabilities such as surf-riding/broaching. The major limiting factor for high-speed planing craft in waves is however generally the hydrodynamic slamming loads and the related vertical impact accelerations occurring at violent wave encounters (Savitsky & Koelbel 1993). These vertical accelerations might impair the ability of the crew to carry out their duties and have adverse effects on their health and safety (e.g. Begovic et al 2015, de Alwis & Garme 2017). If not considered properly these impact loads might also impair the functioning of machinery and other on-board systems and the integrity of the hull structure (IMO 2008).

The safety philosophy of the IMO HSC Code is that an appropriate safety level can be achieved based on active management and reduction of risk in combination with the traditional philosophy of passive in-built safety (IMO 2008). Some of the key elements in this risk management approach are the formulation and application of *operational limitations* in terms of service area restrictions (typically maximum distance to safe port) and speed reductions in heavy weather, and *operational guidance* to the crew typically in terms of signboards in the wheelhouse stipulating the maximum allowable speed as function of significant wave height (IMO 2008, DNVGL 2015).

As described for example in Savitsky & Koelbel (1993), a number of different aspects can be seen as limiting the speed in waves. If all these aspects are combined, the allowable speed-wave height envelope can be formulated as illustrated for a hypothetical high-speed planing craft in Figure 1.

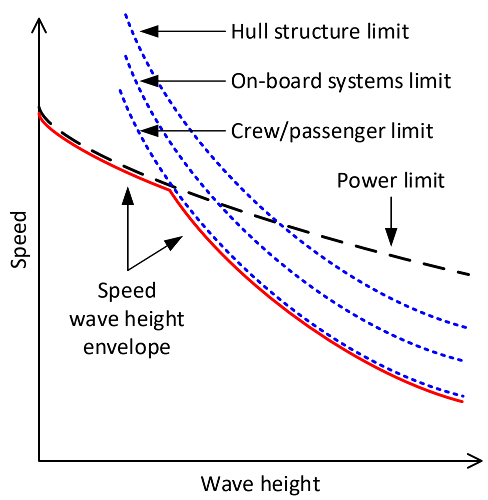

Figure 1: Different aspects limiting the speed in waves and definition of the speed-wave height envelope.

For the hypothetical craft in Figure 1, the added resistance in waves in relation to the installed power would, as seen, result in involuntary speed reduction up to a certain wave height. In higher waves the vertical accelerations would be intolerable to the crew, and to enable their continued on-board duties and to protect their health and safety, the crew would voluntarily reduce the speed. The installed power and crew tolerance related speed reductions would in this case, as seen in Figure 1, give safety margins for the on-board systems and the hull structure. Some safety margins might be good. However, if the structure is designed to withstand loads that are much larger than the crew/passengers can tolerate or the installed power can generate, that would imply an over-dimensioned and unnecessarily heavy structure, which in turn would imply a less efficient craft.

It is in the hands of the designer to create good balance between safety and performance for the craft in its intended operation, by balancing the installed power, the crew/passenger and systems situation and tolerances, and the structure load carrying capacity. The speed-wave height envelope could be formulated either as a target for, or as a consequence of, the design decisions. It is then in the hands of the crew to operate the craft with active consideration of the stipulated speed-wave height envelope, to achieve as high performance as possible without endangering safety and functionality.

The IMO high-speed craft safety philosophy and related classification rules (e.g. DNVGL 2015, RINA 2009) certainly opens up for design optimization. A craft could for example be optimized for its "normal" operating conditions taking into account well informed speed reductions in more rarely occurring rougher conditions. In practice, however, designers' abilities to create such balanced and optimized designs, and crews' abilities to judge the operational conditions and operate the craft within detailed speed-wave height limits, are still rather limited. There is also a large knowledge gap regarding the effects on health and work ability for high-speed craft crew in rough conditions (e.g. de Alwis & Garme 2017).

An obvious limitation is in the prevailing methods for assessing slamming loads and vertical accelerations in waves. Here state-of-the-art is still the semi-empirical formulas developed by Savitsky & Brown (1976) and Allen & Jones (1978) as implemented in classification rules such as DNVGL (2015), RINA (2009), and ISO (2008). These formulas are good in that they are well established and that they, with very limited effort and resources, enable determination of design pressures and speed-wave height limit curves that can be provided as operational guidance to the crew. However, the limitations of these methods are obvious and their accuracy has been extensively questioned (e.g. Koelbel 1995, Rosén et al 2007, Grimsley et al 2010, McCue 2012, Bowles & Soja 2014, Razola et al 2014, Razola et al 2016, Begovic et al 2016).

An obvious potential for improvement would be to use direct assessment methods, either experimental or numerical or a combination. Due to the high speed, the high level of non-linearity, the transient nature of the loads and responses, and the randomness of the waves and responses, the situation of a high-speed planing craft in waves is however very challenging to model, experimentally as well as numerically.

This paper presents lessons learned from extensive model experiments performed at the University of Naples "Federico II" (UNINA) and simulations performed at the Royal Institute of Technology (KTH). The prevailing semi-empirical methods for assessing high-speed craft dynamics in waves are scrutinized and challenges and opportunities related to establishing alternative direct assessment methods are discussed. Finally the presented findings are discussed in perspective of the IMO high-speed craft safety philosophy and the Second Generation Intact Stability Criteria.

2. EXPERIMENTS

The experimental campaign, basis of this work, has been presented extensively in Begovic et al (2012, 2014, 2016). Here some important information is recalled. The tested model has a mathematical monohedral hull with parabolic bow and a constant deadrise angle of 16.7 deg. The deadrise is chosen as representative for modern planing hull design trends for the aft part. The parabolic bow section makes the model comparable with the Fridsma (1971) models having 10, 20 and 30 degrees. Many previous experiments have been performed in sea states which could be considered to be too severe for small high-speed planing craft, typically $H_{1/3}/B_C$ = 0.222, 0.444 and 0.666. This experiment is hereby filling a gap by focusing on $H_{1/3}/B_C$ lower than 0.2.

Seakeeping tests were performed at the University of Naples "Federico II" Towing Tank (135m x 9m x 4.2m). Before performing seakeeping tests, the model centre of gravity location and relevant radii of gyration were measured by an inertial balance and are reported in the Table 1. The model was towed at constant speed in head seas, free to heave and pitch and restrained for all other motions and connected to the towing carriage through a mechanical arm apt to measure heave and pitch, as shown in Figure 2. Two Cross Bow CXL04GP3-R-AL accelerometers were installed: one at the CG position and one at the bow. Encountered waves were measured by two BAUMER UNDK 301U6103/SI4 ultrasonic gauges, the former located on the side at LCG, the latter at centreline, 3.48 m ahead from CG. Four different speeds have been tested: 3.40, 4.60, 5.75 and 6.30 m/s, corresponding to volumetric Froude numbers: 1.92, 2.60, 3.25 and 3.57. All experiments were performed in irregular waves representing a JONSWAP sea spectra with target significant wave height 0.055 m, spectral peak period 1.17 s, and peak factor 3.3. All data were sampled at 500 Hz.

Table 1: UNINA model principal characteristics.

Length (over all)	L	m	1.900
Width (chine)	B	m	0.424
Deadrise	β	deg	16.7
Displacement	Δ	kg	32.56
Draught (aft perp.)	T	m	0.096
Static trim	τ	deg	1.66
Long.centre of gravity	LCG	m	0.697
Vert.centre of gravity	VCG	m	0.143
Pitch gyradius	$k_{55\text{-}air}/L$	-	0.307

Figure 2: UNINA model experimental set up (photo at model speed V = 5.75m/s).

3. SIMULATIONS

Simulations are here performed on the same craft using a non-linear time-domain strip method developed at the KTH Royal Institute of Technology (Garme 2005, Garme & Rosén 2003). The simulation approach is in the tradition of Zarnick (1978). The 2-d hydrodynamic coefficients are initially determined by a panel method for a set of different draughts, here 121. The coefficients in the equations of motions are up-dated at every time step during a predictor-corrector time-stepping procedure and the solution describes the non-linear situation of the planing hull in head waves. During the simulation, pre-calculated hydrostatic and hydrodynamic coefficients are collected with reference to the momentary sectional draught. The hydrostatic coefficients are defined relative to the wave surface level and the dynamic coefficients relative to the piled-up surface level. The hydrodynamic section loads are determined as the momentary time rate of change of fluid momentum both for chines-wet and chines-dry parts of the hull. The decrease of pressure close to the transom stern, not caught by the 2-dimensional theory, is treated by a semi-empirical correction of the load distribution. The simulation model has been successfully validated for speeds corresponding to Froude number based on ship width, C_v, larger than 2. Simulations are here performed with a time step 0.0016 s in the same speeds and wave conditions as the experiments. Self repetition is avoided in the realization of the irregular waves.

The code is not optimized for speed and the cpu-time, for modelling HSC in irregular waves by running the code on a standard computer, is in the order of 10 times real-time. Nevertheless, it is considered absolutely feasible to lessen this to a one-to-one relation, simply by efficient programming in a faster language.

4. SOME OBSERVATIONS FROM THE EXPERIMENTS AND SIMULATIONS

The purpose here is to highlight some important observations from the performed experiments and simulations and discuss the capabilities of these two modelling approaches.

According to ITTC (1999) a minimum of 100 wave encounters is recommended for testing high-speed craft in irregular head seas. Due to the high speed and the time needed for accelerating and decelerating the model, even in a long towing tank a large number of repeated test runs are required to achieve appropriate number of wave encounters. In the here presented experiments repeated tests resulted in 280 wave encounters at constant speed of 3.40 and 4.60 m/s, 230 for a speed of 5.75 m/s, and 160 for a speed of 6.30 m/s. When evaluating the results the constant speed parts of the different runs have been spliced together for each speed. The here used simulation model has been developed with concern regarding the trade-off between accuracy and computational effort to allow for long simulations in irregular waves. In the here presented study the simulation time in irregular waves is 1000 s giving more than 700 wave encounters in each speed.

In Table 2 and Table 3 the standard deviation and the mean values of the peak-to-peak zero-crossing amplitudes of the heave and pitch responses are presented. As seen the agreement between the experiments and the simulations is very good for pitch and reasonably good for heave, particularly for the peak-to-peak amplitudes. For the heave at 4.60 m/s the simulated mean peak-to-peak amplitude is however distinctly larger than the experimental.

Table 2: The heave standard deviation, $\eta_{3\sigma}$, and the mean peak-to-peak amplitudes, η_{3m}, from experiments and simulations. Relative errors are also presented.

v [m/s]	$\eta_{3\sigma,exp}$ [m]	$\eta_{3\sigma,sim}$ [m]	E_σ [%]	$\eta_{3m,exp}$ [m]	$\eta_{3m,sim}$ [m]	E_m [%]
3.40	0.0040	0.0040	0.0	0.0096	0.0096	0.0
4.60	0.0042	0.0050	19.0	0.0099	0.0115	16.2
5.75	0.0044	0.0052	18.2	0.0108	0.0115	6.5
6.30	0.0046	0.0053	15.2	0.0111	0.0116	4.5

Table 3: The pitch standard deviation, $\eta_{5\sigma}$, and the mean peak-to-peak amplitudes, η_{5m}, from experiments and simulations. Relative errors are also presented.

v [m/s]	$\eta_{5\sigma,exp}$ [m]	$\eta_{5\sigma,sim}$ [m]	E_σ [%]	$\eta_{5m,exp}$ [m]	$\eta_{5m,sim}$ [m]	E_m [%]
3.40	0.499	0.464	-7.0	1.120	1.180	5.4
4.60	0.478	0.462	-3.3	1.157	1.139	-1.6
5.75	0.427	0.429	0.5	0.977	1.003	2.7
6.30	0.430	0.424	-1.4	0.999	0.973	-2.6

The characteristic transient nature of the slamming related vertical accelerations for high-speed craft in waves is seen in Figure 3 and Figure 4 which show examples from experiments and simulations for a model speed of 5.75 m/s. It should be noted that the experiments and simulations are performed in different realizations of the same sea state. Direct comparison between the measured and simulated signals in the time domain is therefore not relevant. Instead statistical analysis is required for detailed comparison between experiments and simulations.

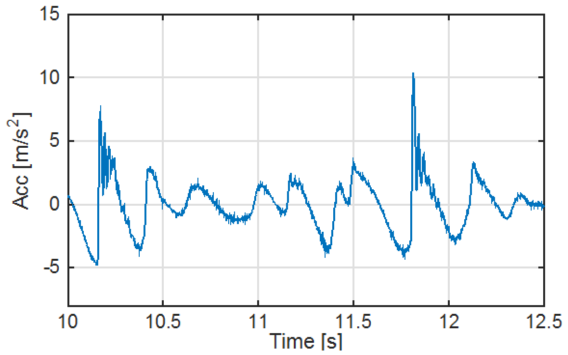

Figure 3: Example of vertical acceleration data from experimental measurements at v=5.75 m/s.

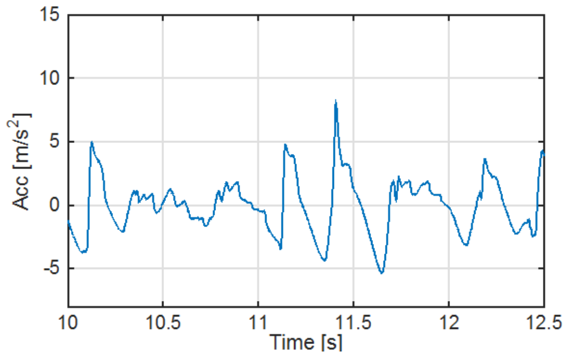

Figure 4: Example of simulated vertical acceleration data at v=5.75 m/s.

The vertical acceleration process for high-speed craft in irregular waves is generally characterized in terms of statistical peak fraction averages, such as the average of the largest 1/10th or 1/100th of the peak acceleration values. Defining and identifying peaks related to rigid body acceleration in signals as the ones in Figure 3 and Figure 4 is far from trivial. In this study the peak values are here identified according to Razola et al (2016) which in turn principally follows the Standard-G approach by Riley et al (2010). The vertical threshold value is set to the standard deviation of the acceleration process, and the horizontal threshold is set based on the encounter frequency.

The convergence of various statistical measures are exemplified in Figure 5 for simulations at v=5.75 m/s. The experimental results show a similar pattern. As seen the average of the largest 1/100th peak values would require 500 or more peaks for convergence. This is far more than what is generally achieved in experiments. The lower level averages (1/3rd and 1/10th) can however be considered to reach reasonable convergence with the number of wave encounters realized in the here presented experiments, maybe with exception from the average of the largest 1/10th peak values at the highest speed where only 160 wave encounters are measured. More on statistical analysis of high-speed craft vertical impact accelerations can for example be found in Razola et al (2016), Begovic et al (2016), and Katayama & Amano (2015).

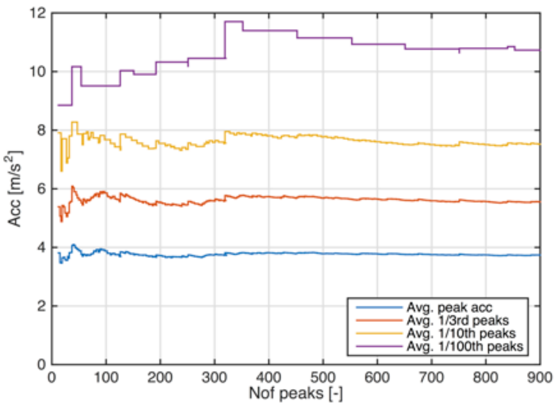

Figure 5: Convergence of the statistical measures of the peak acceleration process for the simulated data for *v*=5.75 m/s.

Another challenge is the non-rigid body vibrations which are very difficult to completely eliminate in experiments due to flexibilities in the model structure and vibrations in the towing carriage. Such vibrations are for example seen in Figure 3. According to the frequency spectra in Figure 6 these vibrations are mainly found in the frequency range ~30-40 Hz. Unfortunately this is in the same time scale as the slamming process and typical rise times of the vertical acceleration signal at impact. This affects the experimental data where the peak values to some extent will be amplified by the vibrations.

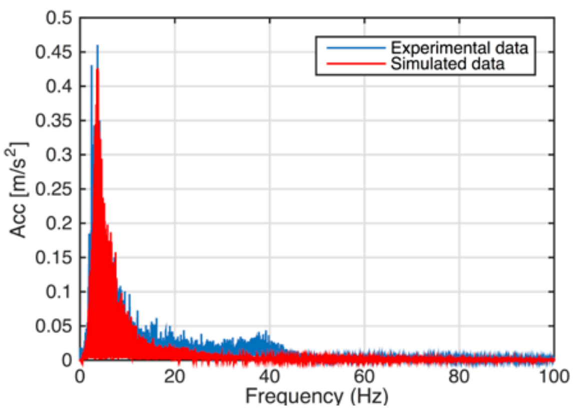

Figure 6: Single-sided frequency spectrum for the experimental and simulated acceleration data for a speed of *v*=5.75 m/s.

However, by considering the fact that the numerical model only simulates the rigid body motions, the simulated and experimental data can be combined to determine an appropriate frequency level for low-pass filtering of the experimental data. In Figure 7 peak acceleration statistics for a model speed of 5.75 m/s is displayed as function of low-pass filtering cut-off frequency using a 4th order Butterworth filter. As seen, for the simulated signals the statistics are principally unaffected for cut-off levels down to 25-30 Hz. The largest peaks might be affected by filtering on that level, however only to a degree that is not captured by the here studied statistics. On the other hand the experimental statistics is clearly affected at cut-off levels below 60 Hz. Based on such analysis a low-pass cut-off level of 30 Hz can be concluded to be appropriate for these experiments. An approach for eliminating towing carriage vibrations could be to use a free-running model as demonstrated in Savitsky (2016).

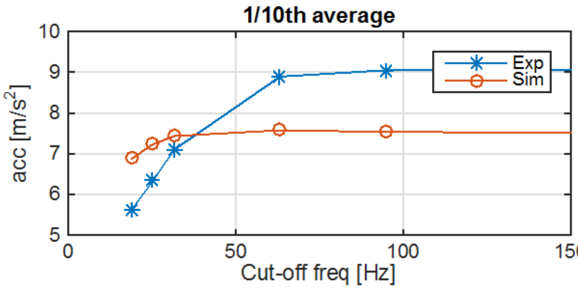

Figure 7: Effect of the low-pass filtering frequency on the acceleration peak statistics for a speed of *v*=5.75 m/s.

In Figure 8 the peak fraction average statistics is compared between experimental data low-pass filtered at 30 Hz and unfiltered simulated data. As seen the agreement is good for the higher speeds where the differences are in the order of a few percent. The lower speed *v*=3.60 m/s corresponds to a Froude beam number C_v=1.77 which is smaller than the validated speed regime for the simulation model, C_v>2.0. This could explain the difference between the experiments and simulations at this speed.

The results from this limited study are encouraging and indicates promising capabilities of the presented experimental setup and the numerical approach in capturing the slamming related vertical acceleration process for high-speed planing craft in waves. More thorough evaluations will come in a later paper.

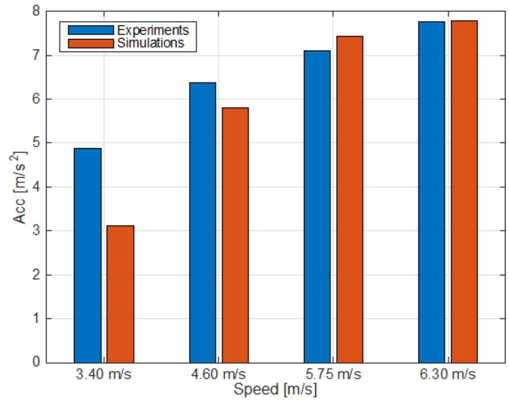

Figure 8: Comparison of the average of the 1/10th highest acceleration peaks from experiments low-pass filtered at 30 Hz and unfiltered simulations.

5. SPEED-WAVE HEIGHT LIMITS

The state-of-the-art approach for deriving speed-wave height limit curves as in Figure 1, is to use formulas relating craft vertical acceleration, speed and wave height, provided by classification societies. These formulas can all be derived back to the semi-empirical formula presented in Savitsky & Brown (1976), which in turn was derived based on the model experiments by Fridsma (1971). According to Savitsky & Brown the average of all acceleration peak values, when a high-speed planing craft is operating in V knots in irregular head seas with a significant wave height $H_{1/3}$, is given by

$$a_{1/1} = 0.0104\left(\frac{H_{1/3}}{B} + 0.084\right)\frac{\tau}{4}\left(\frac{5}{3} - \frac{\beta}{30}\right)\left(\frac{V}{\sqrt{L}}\right)^2 \frac{L/B}{C_\Delta} \quad (1)$$

where L, B, τ, β, and C_Δ are craft length, beam, trim, deadrise and load coefficient. Savitsky & Brown assumed that the acceleration peak process is exponentially distributed and hereby expressed the statistical average of the 1/Nth highest peak values as

$$a_{1/N} = a_{1/1}\left(1 + \log_e N\right) \quad (2)$$

As an illustration of the similarities between today's classification rule formulas and the Savitsky & Brown source work, for example the formula by DNVGL (2015) is expressed as

$$a_{cg} = \frac{k_h g_0}{1650}\left(\frac{H_{1/3}}{B} + 0.084\right)(50 - \beta)\left(\frac{V}{\sqrt{L}}\right)^2 \frac{LB^2}{\Delta} \quad (3)$$

A comparison between different formulas is made in Figure 9 for the craft studied in the experiments and simulations in the previous sections, here however in full-scale where a scale factor 1:10 gives a craft length 19 m, significant wave height 0.55 m, and speeds 21, 28, 35, 39 kn.

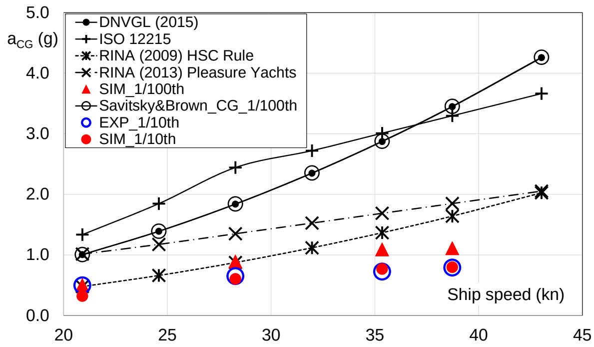

Figure 9: Vertical acceleration at CG in head seas as function of speed according to Savitsky & Brown, various scantling codes, and from the presented experiments and simulations.

The Savitsky & Brown results are here presented on the 1/100th average level. The DNVGL (2015) High-Speed and Light Craft Rules do not specify what statistical level their formula is corresponding to. Figure 9, however, makes it obvious that the DNVGL formula is corresponding exactly to Savitsky & Brown on the 1/100th level. The RINA (2009) HSC Rules on the other hand explicitly defines a design vertical acceleration on the 1/100th average level. However, in Figure 9 it can be observed that the RINA (2009) results are far below the Savitsky & Brown results on the 1/100th level. It can be shown that the RINA (2009) results instead correspond to Savitsky & Brown on a 1/5th average level. Also the RINA (2013) Rules for Pleasure Yachts are claimed to be on the 1/100th average level. As seen however these results are between the Savitsky & Brown 1/100th and RINA (2009) results. The ISO (2008) formula is similar to the Savitsky & Brown formula up to a_{cg}=3 g, however with the significant wave height fixed to $H_{1/3}$=L/10 which is much larger than the 0.55 m here used in the other formulas.

Let's consider that the hull structure of a certain high-speed craft (for some reason) should be designed with respect to an overall design acceleration/load factor a_{cg}=2g. The corresponding speed-wave height limit curve can then easily be derived by using class formulas, such as equation (3), simply by substituting the constant limiting acceleration a_{cg}=2g and extracting V as function of $H_{1/3}$ from the formula. From Figure 9 and the discussion above it is however obvious that the same design acceleration/load factor would result in very different speed-wave height limits from the different classification rule sets.

As mentioned in the introduction, several previous studies have questioned the Savitsky & Brown method, in particular the assumption that the acceleration peak values would be exponentially distributed. For example in Razola et al (2016) it is shown that calculation of the average of the 1/100th highest acceleration peaks, $a_{1/100}$, by scaling the average of all peaks, $a_{1/1}$, according to equation (2), would give much higher values than if calculated directly from the 1/100th highest acceleration peaks. In the DNVGL (2015) rules this "error" is however fortunate, whether conscious or not, since the Allen & Jones (1978) design slamming pressure as implemented in the DNVGL (2015) rules otherwise would have been significantly under-predicted if the average of the 1/100th highest acceleration peaks would have been correctly calculated. Whether the observed down-scaling of the RINA (2009) accelerations, compared to the Savitsky & Brown 1/100th average, is a conscious consideration of the error in the Savitsky & Brown exponential distribution assumption is not obvious. However, comparing the Allen & Jones (1978) design slamming pressure implementation in DNVGL (2015) and RINA (2009) and the difference in their respective implementations of the Savitsky & Brown accelerations, again makes it obvious that the design acceleration and the related design pressures have different meanings between different classification societies. As long as these different formulas are only used within each rule set it might be ok. However, what actual safety level that is achieved is far from explicit and might be debated.

The previous section demonstrated promising capabilities of the presented experimental and numerical approaches in modelling the characteristics of high-speed planing craft in waves. This might indicate an opportunity to replace the prevailing semi-empirical methods, partly or completely, with direct assessment methods. Applying simulations or experiments in the design of high-speed planing craft however still involves a number of challenges.

As seen, Figure 9 also includes the results from the here presented experiments and simulations on a 1/10th average level from Figure 8 and also simulated values on a 1/100th level. As seen these values, even the simulated values on the 1/100th level, are significantly lower than the corresponding outcomes from the semi-empirical rule formulas, except from the RINA (2009) results which are in parity with the experimental and numerical results at lower speeds. One obvious explanation for these differences is that the experiments and simulations have only been performed in one sea state where the match between wave mean period and craft speed might not correspond to the worst regarding response resonance. It should also be noted that the here studied wave height is rather low. Another reason for the differences between simulation/experiments and the semi-empirical methods is the above described "error" in the way Savitsky & Brown and the rule formulas calculate the statistical fraction averages resulting in over-prediction. All these aspects must be very carefully considered if the prevailing Savitsky & Brown based semi-empirical approach should be replaced or complemented by experiments or simulations.

Another challenge is the extensive effort involved in applying direct assessment methods compared to semi-empirical methods. Deriving just one point on a speed-wave height limit curve, would require a substantial amount of iterative simulations or experiments to find the speed for each wave height that corresponds to a certain limiting acceleration, e.g. the average of the highest 1/100th acceleration peaks equal to 2g. Additional simulations or experiments would be needed to also take different wave mean periods into consideration, either finding the one resulting in the largest responses or deriving a two-dimensional speed/wave height/wave period limit curve/surface.

Considering that more than 500 wave encounters are required for convergence of the 1/100th average, as observed in the previous section, it can be concluded that a purely experimental approach would be prohibitively expensive. However, as mentioned, the here used simulation model is a rather simple non-linear strip method that has been developed with concern regarding the trade-off between accuracy and computational effort to allow for long simulations in irregular waves. With some further improvements of the code efficiency it should therefore be realistic to actually go through with the number of simulations needed for deriving speed-wave height limits.

An interesting option might be to use a combined approach. The first step could here be to use simulations to derive a speed/wave height/wave period limit curve/surface for an acceleration limit expressed in terms of the 1/10th average. The second step could be to perform experiments corresponding to a few points on the simulation based limit curve/surface. The outcome from the experiments could then either be used to confirm the simulations or to tune the simulation based limit curve/surface if the experiments are considered to be more accurate than the simulations. Finally the simulations could be used to further scale the limit curve/surface to represent an acceleration limitation in terms of another statistical measure such as the 1/100th average or an extreme value.

6. CONCLUDING REMARKS & OUTLOOK

The paper has presented some lessons learnt and results from an extensive experimental campaign and simulations performed on a high-speed planing craft in waves. Though rather limited, the study is encouraging and indicates promising capabilities of the presented experimental setup and the numerical approach in capturing the vertical impact acceleration processes for high-speed planing craft in waves. The prevailing semi-empirical approach and related classification rule formulas for assessing high-speed craft vertical accelerations, have been reviewed and scrutinized and a number of questions regarding the validity of these methods and the resulting safety levels have been raised. Challenges related to establishing direct assessment methods are highlighted and opportunities with a combined experimental-numerical approach are discussed.

The IMO high-speed craft safety philosophy has high and modern ambitions, opening up for complementing the traditional philosophy of passive in-built safety with active management of risk. By applying *operational limitations* and *operational guidance* there is a potential to achieve optimized designs with appropriate safety levels. Still, as demonstrated in the paper, the prevailing semi-empirical methods for assessing high-speed craft dynamics in waves, and providing guidance to crew, are rather primitive and their validity could be questioned. Based on these observations, and the findings and discussions in the paper, a number of questions could be raised for further consideration:

a) Is high-speed planing craft design, based on the prevailing semi-empirical methods, nothing but qualified guess work?
b) How well do we actually know the current safety levels for high-speed craft in waves?
c) What would be an appropriate safety level?
d) Are the currently available direct assessment methods mature for being practically applied in high-speed planing craft design? If so, would a combined experimental-numerical approach be feasible?
e) How should the safety levels be assessed and related to the current safety levels if/when direct assessment methods are established?
f) Despite the highlighted limitations and deficiencies in the prevailing semi-empirical methods, the IMO high-speed craft safety philosophy is actually in place and applied both by designers and crews. Could something be learnt from this when establishing the *Second Generation Intact Stability Criteria*, for example regarding risk management, the concepts *operational limitations* and *operational guidance*, and regarding the choice of methods and approaches for direct assessment and formulation of operational guidance?

The authors are looking forward to discussing these issues and other aspects of the paper with the participants at the 16th International Ship Stability Workshop.

ACKNOWLEDGEMENTS

This work has been supported by the Swedish Mercantile Marine Foundation and the Swedish Maritime Administration which are both gratefully acknowledged.

REFERENCES

Allen R G, Jones R R, 1978, “A Simplified Method for Determining Structural Design Limit Pressures on High Performance Marine Vehicles”, Proceedings of the AIAA/SNAME Advanced Marine Vehicle Conference.

Begovic E, Bertorello C, 2012, “Resistance Assessment of Warped Hull Forms”, Ocean Engineering Vol. 56, pp. 28-42.

Begovic E, Bertorello C, Pennino S, 2014, “Experimental Seakeeping Assessment of Warped Planing Hull”, Ocean Engineering Vol. 83, pp. 1-15.

Begovic E, Bertorello C, Pennino S, Piscopo V, Scamardella A, 2015, “Experimental Assessment of Comfort on Board Planing Hulls”, Towards Green Marine Technology and Transport, pp. 493–500.

Begovic E, Bertorell C, Pennino S, Piscopo V, Scamardella A, 2016, “Statistical Analysis of Planing Hull Motions and Accelerations in Irregular Head Sea”, Ocean Engineering, Vol. 112, pp. 253-264.

Bowles J, Soja J, 2014, “Comparative Analysis of Common Methods for Predicting Vertical Acceleration of Hard Chine Planing Monohulls including Correlation to Hydrodynamic Model Test Data”, 4th Cheasapeake Powerboat Symp., US.

de Alwis M P, Garme K, 2017, ”Adverse Health Effects and Reduced Work Ability due to Vertical Accelerations in High-Performance Marine Craft Personnel”, 16th Int. Ship Stability Workshop (ISSW2017), Belgrade, Serbia.

DNVGL, 2015, “Rules for Classification, High speed and light craft”, Part 3.

Fridsma G, 1971, “A Systematic Study of the Rough Water Performance of Planing Boats. Irregular Waves – Part II”, Stevens Institute of Technology, March 1971, report SIT-DL-71-1495

Garme K, Rosén A, 2003, “Time-Domain Simulations and Full-Scale Trials on Planing Craft in Waves”, International Shipbuilding Progress, Vol.50, No.3.

Garme K, 2005, “Improved Time-Domain Simulation of Planing Hulls in Waves by Correction of the Near-Transom Lift”, International Shipbuilding Progress, Vol.52, No.3.

Grimsley J, Liu Y, Hou G, 2010, “An Examination of the Statistical Behavior of Planing Craft Peak Vertical Accelerations in Irregular Waves”, 29th American Towing Tank Conference: pp. 31-39, US.

IMO, 2008, “International Code of Safety for High-Speed Craft”.

ISO, 2008, “Small craft – Hull construction and scantlings – Part 5: Design pressures for monohulls, design stresses, scantlings determination”, ISO 12215-5.

ITTC, 1999, “Recommended Procedures and Guidelines, Testing and Extrapolation Methods, High Speed Marine Vehicles Seakeeping Tests”, ITTC 7.5-02-05-04.

Katayama T, Amano R, 2015, "An Experimental Study on the Characteristics of Vertical Acceleration on Small High Speed Craft in Head Waves", 12th Int. Conf. Stability of Ships and Ocean Vehicles (STAB2015), pp. 587-597, UK.

Koelbel J G, 1995, “Comments on the Structural Design of High Speed Craft” Marine Technology 32(2), pp. 77–100.

McCue L, 2012, “Statistics and Design Implications of Extreme Peak Vertical Accelerations from Slamming of Small Craft”, Journal of Ship Production and Design 28(3), pp.112–127.

Razola M, Rosén A, Garme K, 2014, “Allen and Jones Revisited”, Ocean Engineering, Vol.89, pp.119–133.

Razola M, Olausson K, Garme K, Rosén A, 2016, “On High-Speed Craft Acceleration Statistics”, Ocean Engineering, Vol.114, pp.115–133.

Riley R M, Haupt K, Jacobson D, 2010, “A generalized approach and interim criteria for computing A1/n accelerations using full-scale high-speed craft trials data”, Technical report: NSWCCD-23-TM-2010/13.

RINA, 2009, ”RINA Rules for the Classification of High-Speed Craft”.

RINA, 2013, “RINA Rules for the Classification of Pleasure Yachts, Part B Hull and Stability”.

Rosén A, Garme K, Kuttenkeuler J, 2007, “Full-Scale Design Evaluation of the Visby Class Corvette”, 9th Int. Conf. on Fast Sea Transportation (FAST'07), China.

Savitsky D, Brown P W, 1976, “Procedures for Hydrodynamic Evaluation of Planing Hulls in Smooth and Rough Water”, Marine Technology, Vol.13, No.4.

Savitsky D, Koelbel J G, 1993, “Seakeeping of Hard Chine Planing Hulls”, Society of Naval Architects and Marine Engineers (SNAME), Technical Research Bulletin No. 42.

Savitsky D, 2016, “Direct Measure of Rigid Body Accelerations for Wave Impact of a Planing Hull”, Journal of Ship Production and Design, Vol. 32, No. 4, pp. 235–244.

Zarnick E E, 1978, “A Nonlinear Mathematical Model of Motions of a Planing Boat in Regular Waves”, David W. Taylor Naval Ship R&D Center, USA.

This page is intentionally left blank