Abstract
The continuous push towards improved technologies allows designers to resolve the naval architecture problems with a higher reliability and to optimize designs. In this process it becomes increasingly important to recognize that most statutes and the Industry practice at large have depended on a few criteria to cover a very large number of hazards. Tools such as hazard identification and risk are becoming a dominating aspect of design in general and naval architecture in particular.

The paper considers several examples of stability failures that can be called unconventional. Attempts to resolve the root cause of these failures may lead to a solution incompatible with the purpose of ship or an offshore installation.

Keywords
Stability of ships; Stability of offshore installations; Stability failure; Numerical simulation; Probabilistic interpretation.

Introduction
The notable lack of stability statutes until the second half of the 20th Century, may suggest that most vessels were designed without stability standards. While this is not true, the criteria were often applied differently by each designer, or each administration. The relatively simple tools for evaluation stability required reliable, simple and much generalized methods. This practice leads to criteria that offered comfortable margins to account for novel conditions or unexpected hazards.

Part of the misconception is that the focus of naval architecture seems to apply to a relatively narrow variety of types of vessels. This is only partially true when we see the variety of highly specialized vessels, and that technology has allowed us to optimize each design. Also, a part of this development is the loss of applicability of the simple tools where “one criterion fits all.”

Not long ago, a 0.30 metacentric height for merchant vessels seem to lead to satisfactory stability. This remained true only as long as design conditions and other practices kept the vessel within certain bounds.

The optimization of each design is often at the expense of built-in safety and inherent reliability. Designs moved from a few “multi-purpose” vessels, to the highly specialized. Such a shift created new types of vessels that in the process of optimization, created risks that demanded important corrections giving way to new statutes and design methods.

Incidents with a common root cause were identified in many areas: cargo shifting in bulk carriers, lolling of double skin tankers, and unusual angles of roll in containerships caused by parametric resonance are just a few examples of the failure of conventional stability standards when applied to emerging technologies. In that light, designers and regulators became increasingly reactive as the innovations increased in frequency preventing the long-winded analysis that can foresee the consequence of each advance.

While most of such unexpected hazards are resolved by way of conventional stability methods, many may require more sophisticated applications. The ones that fall into the last group, such as parametric roll, surf riding and broaching, pure loss of stability on following seas, green water, will inexorably push for simpler solutions that fit within the time available to deliver reliable designs.

Appearance of a Gap
The thousand year long history of ship design seems to have been recycled in the last 50 years in the new environment of oil exploration and production at sea. The first such venture in 1947 took a wild leap into jack-up and semi-submersibles in just ten or so years. The definition of deep water grew from a few feet to ten thousand feet in such a short time that some of those pioneers are still teaching the young with stories that require no exaggeration to be “tall”.

Offshore vessels can be categorized in many groups, service, exploration, production and for each category, the types of
hulls change from the conventional hull to the almost bizarre. The most frequent types are grouped into surface type, semi-submersibles, self-elevating. Beyond those types, the novel designs are a daily event.

The earliest experience offshore was all around exploratory drilling. If the exploration was successful, the production of oil was from fixed platforms and the production drilling was carried out from the platform. Production of oil from a floating platform had to wait until 1958.

Conventional vs. Unconventional Modes of Failure

The parametric roll represents an example for an unconventional mode of stability failure. Why?

Parametric roll was known to Naval Architects as a mode of stability failure since the late fifties [Paulling and Rosenberg 1959], however it was considered to be a problem for small and medium-size vessel in following seas. An accident with post-panamax container carrier in 1998 [France et al. 2003] brought this phenomenon into the focus from completely different point of view. The parametric roll now is seen as a problem for large containerships in near head seas.

Vulnerability of modern containerships to parametric resonance is a result of design requirements for relatively high speed and volumetric capacity. A hull form that meets both these requirements will have significant vertical variation in waterline width. This inevitably leads to a large variation of stability in head or following seas and therefore creates susceptibility for parametric roll.

First of all, should the parametric roll be considered as a stability or general seakeeping issue if a vessel did not capsize?

If a vessel is designed for unrestricted service, the motions and loads are assumed based on certain probability of wave encounter. Similar approach is being taken for container lashing (ABS 1988). Parametric roll may produce accelerations and angles that are unpractical to design against (see next section), so parametric roll is generally not acceptable and has to be avoided – similar to heeling beyond down-flooding angle or capsizing.

So the conditional boundary between seakeeping and stability in waves can be drawn as follows:

Seakeeping analysis deals with moderate- and large-amplitude ship motions and accelerations. The purpose of seakeeping analysis is to find out what would be the loads from these motions and accelerations and design the vessel to better withstand them.

Analyses of stability in waves deals with extremely large-amplitude motions and accelerations. The purpose of analysis is to find the way to avoid them.

Solutions Incompatible with Purpose

The ultimate reason for parametric roll is the change of stability in waves caused by a significant widening of hull above the calm water waterline. The simplest solution then is to remove this reason by avoiding such changes accomplished by making the water-plane more full-formed and limiting bow flares and stern overhang. This “solution”, though it looks simple, is, in fact incompatible with the very purpose of a container carrier: transport relatively light cargo (volumetric capacity needed) with relatively high speed (waterline needs to be slim). Therefore the solution needs to be found beyond traditional thinking – “find the cause of failure; then remove it”.

A jack-up rig during tow operation represents an evident stability hazard as its freeboard is extremely low (Fig. 1 and Fig. 2). The evident solution based on conventional naval architecture wisdom is to require increasing of the freeboard. This, however will increase the weight of the pontoon and make it difficult (or even impossible) for the leg structure to support such a weight when the rig is in normal operation. Again, “remove the cause of failure” does not work here.

Fig. 1: Jack-up in tow

Fig. 2: Green water inflow on the deck of jack-up during tow operation
Practical Solutions

While elimination of parametric roll on the design stage seems not to be feasible, combination of design and operational measures can mitigate the risk.

Changing the hull shape at stern towards more of a “v-shape” noticeably decreases chances for parametric roll (Levadou and van’t Veer 2006). This source also shows the positive effect of the bilge keels and the anti-rolling fins. Efficiency of the fins, however, depends on speed, which may be low in stormy conditions when the parametric resonance presents the most serious danger. Effect of anti-rolling tanks does not depend on speed, however, and so far there was only numerical simulation data in reference to their efficiency against parametric roll (Shin, et al. 2004).

SLF 50/4/4 recognizes that is not possible to exclude the possibility of parametric roll on the design stage, so a combination of the measures on the design and operation stage is needed. ABS (2004) proposes a formal verification of susceptibility, available as soon as lines are developed. Once the susceptibility has been established, the severity analysis allows the estimation as to what speeds could produce dangerous parametric roll response. Finally numerical simulation is used to produce ship-specific on-board guidance to be used for course planning, see example below (Fig. 3).

This polar plot shows estimates of expected maximum roll angles caused by parametric as well as synchronous resonance. The roll angles are presented as a function of speed and relative wave heading (zero being head seas while 180 degrees corresponds following seas). Concentric circles represent speeds from 5 to 25 knots. It is expected that these plots will be used together with the weather routing service, to make an informative decision to proceed through or go around the area of high waves, (Belenky, et al. 2006).

Bridging the Gap

Statutes

While stability standards for conventional ships were slowly growing beyond minimum GM, the Offshore Industry woke up to a great number of incidents, some with dire losses of life, property and damage to the environment. By 1965, Industry concluded that Classification Societies were better suited to develop stability criteria for their very specialized floaters in class. Far more important was the desperate need for an immediate solution, a statement of due diligence, the image of self-regulation. The urgency did not allow for the customary process at IMO and the publication of the 1968 MODU Rules did all that and more.

It is also true that the early MODU Rules addresses a wide set of concerns that are not typical of conventional shipping. Additionally, what the early MODU Rules had in relative clarity, they lacked in finesses. The Rules continued to evolve to address the specific nature of Self-elevating units, Semi-submersibles, Drillships, and Drilling barges.

Apparently, this evolution promoted the gap between conventional shipping and offshore units. However, a closer analysis finds areas where this dichotomy may be in decline.

At the time of the first publication of MODU Rules, only men-of-war and passenger vessels had subdivision standards. Conventional merchantmen had subdivision standards that were based on the length of compartment restrictions and the fitting of double bottoms. MODU, not having conventional proportions, needed “damage” Stability standards.

This visible difference narrowed down in 1992 with the generalization of the probabilistic damage stability criteria. While this did not close the gap, it narrowed it substantially.

Vulnerability Criteria

To counteract the unconventional stability failures (such as those described earlier in the paper), it would be ideal to have an ultimate prediction tool based on physical principles and independent on previous experience expressed in the form empirical or statistical data.

Having a detailed mathematical model of a stability failure could be very helpful in resolving these issues. The problem, however, is proper implementation of these models. In most of the cases the simple mathematical models allowing close form solution are too simplistic to provide a numerical result with sufficient accuracy.

Numerical simulation may provide enough accuracy for practical purposes, but it may be too expensive to use for all ships or offshore installations.

Development and implementation of criteria of vulnerability may be considered as a solution for this situation (Belenky, et al. 2007). Criteria of vulnerability are based on the simple analytical model and should be capable of determining if this particular vessel may be vulnerable to this particular mode of stability failure.

This idea is based on the experience of application of ABS Guide (2004) for parametric roll, where the analysis starts from using ABS susceptibility criteria for parametric roll.
These criteria are based on the Mathieu equation and are capable of determination if parametric roll is possible or not for this vessel.

Although practical importance of these criteria was not that clear from the beginning, it was known that almost all containerships are susceptible to parametric resonance. However, the ability of these criteria to work for any geometry of the hull makes it invaluable for formal assessment. If these criteria are used for VLCC, the answer is that parametric roll is impossible (Shin, et al., 2004).

It seems at this moment similar criteria could be developed for other modes of stability failures. At SLF-50 N. Umeda proposed to use a threshold speed of surf-riding as a basis for vulnerability criterion of broaching.

Development and implementation vulnerability criteria will allow aiming further analysis into problem areas rather that check every scenario possible.

**Numerical Simulation: the Tools**

Numerical simulation is rather a broad term and there is no widely accepted definition for it in engineering practice. In the context of analysis of ship motions and stability, it narrows down to the numerical solution of equations of motions. So the difference mainly comes from the way the forces are found.

If the forces are expressed as analytically or numerically defined functions of state variables and time, the equations of motions become a system of ordinary differential equations of the second order.

A typical example of such simulations is the severity analysis of parametric roll, change GZ curve in regular wave is pre-calculated then substituted into differential equation as a function of roll angle and time.

Another example is code ROLLS (SLF 50/INF.2) that uses the numerical method to solve nonlinear differential equation of roll while other types of motions are taken from frequency domain solution. So the difference mainly comes from the way the forces are found.

Development and implementation vulnerability criteria will allow aiming further analysis into problem areas rather that check every scenario possible.

Numerical Simulation: Challenge of Irregular Waves

Waves at sea are irregular. Rigorous numerical simulation, therefore, is, in fact a Monte-Carlo time-domain simulation of response of a nonlinear dynamical system.

This is a complex engineering problem.

First, input stochastic process has to be presented in a form of time history. Irregular wave information is usually available in a form of spectrum, so inverse Fourier Transform is to evaluate instantaneous wave elevations:

\[
\zeta(t) = \sum_{i=1}^{N} a_i \cos(\omega_i t + \varphi_i)
\]

Here \(a_i\) are amplitudes of wave components, their values calculated from spectrum, \(\varphi_i\) is initial phase of each component; this is a random element of the model with the uniform distribution.

Set of frequencies \(\omega_i\) has significant effect on accuracy of the simulations because it is related with the statistically representative length of the rime history of input process. Equally, it has significant influence on computational efficiency.

It is well known that if equal frequency spacing is used, repeating patterns may be seen in the time history with a period of \(2\pi/\Delta\omega\); popular technique to avoid these patterns is unequal frequency spacing. However, the autocorrelation function still shows numerical errors spread rather then concentrated (Belenky 2005). A larger number of frequencies solve the problem but increases computational cost.

Ergodicity is another challenge. Formally ergodicity is defined as an ability to estimate characteristics (mean, variance, distribution etc) of a stationary stochastic process with one suitably long record. It is known that irregular waves are an ergodic process and response of a linear system on ergodic excitation is also ergodic. Response of a nonlinear system may have a much slower convergence on the variance estimate and therefore may be recognized as not ergodic for practical purposes within the time while waves can still be assumed as a stationary stochastic process. Practical implications of the above include the necessity to consider several records instead of one.

Using several short records instead of one or a fewer long ones also has the advantage in a sense of computational costs. Shorter records require fewer frequencies to generate representative time history so less components need to be summed at every time step; at the same time practical non-ergodicity can be properly accounted for.
The third challenge of irregular wave simulation is probabilistic interpretation of the result which is considered in more details below.

**Probabilistic Interpretation of Numerical Simulations**

To be utilized, numerical simulations should produce a measure of some sort. For example, current ABS uses maximum roll angle observed during certain simulation time: the result is presented in a form of a polar plot, meant to be used for course planning (Belenky et al. 2006).

The advantage of such a measure is its simplicity and clear relation with time of exposure, however a more theoretically robust measure may be considered in the future.

H. Yu proposed using the upcrossing theory for development of the perspective probabilistic measure of parametric roll. The main advantage of the upcrossing theory is that it provides the natural relationship with time of exposure.

Upcrossing is a random event when the value of the process is equal to a positive boundary value and the first derivative of the process is also positive (so the process certainly will cross the boundary from the downside). The number of upcrossings during a given time is a random variable. If upcrossings can be considered independent of each other, their number follows the Poisson distribution, (it could also be said that upcrossings are the Poisson flow of random events).

Probability that \( n \) upcrossing will happen during time \( T \) is expressed as:

\[
P_T(n) = \frac{(\lambda T)^n}{n!} \exp(-\lambda T)
\]  

(2)

\( \lambda \) is the rate or intensity of upcrossings. It is the only parameter in this formula and its meaning is the average number of upcrossings per unit of time. The rate of upcrossing could be found from statistics by counting the number of upcrossing in each record of roll response, then averaging them over all the records and divide it by the length of the record.

The rate of upcrossing can also be found theoretically if joint distribution of roll response and roll rate is known:

\[
\lambda = \int_{\phi} f(\phi = b, \phi) d\phi
\]  

(3)

Here \( b \) is chosen boundary for roll response.

If both roll response and roll rate has normal distribution, this integral can be evaluated symbolically:

\[
\lambda = \frac{1}{2\pi} \sqrt{\frac{V_\phi}{V_\phi'}} \exp \left( -\frac{(b - m_\phi)^2}{2V_\phi'} \right)
\]  

(4)

\( V_\phi' \) and \( V_\phi \) are variance of roll rate and response respectively and \( m_\phi \) is a mean value of roll response

Time between upcrossing is also random number and it is distributed in accordance with exponential law.

\[
f(T) = \lambda \exp(-\lambda T)
\]  

(5)

This allows consideration of partial stability failures (IMO SLF 50/4/4 and Belenky, et al., 2007) related to parametric roll in term of reliability.

Reaching certain roll angle can be defined as a certain type of failure. For example, reaching 22.5 degrees for ABS-classed container carrier may be interpreted as violation of main engine normal operation envelope (ABS 2007). Similar failures could be formulated for lashing, elements of deck structure, container structure etc. Use of the upcrossing theory then allows the evaluating probabilistic characteristics of time before the first failure, which is a conventional reliability characteristic.

Direct application of the upcrossing theory to roll process, however, encounters significant difficulties mainly caused by a highly pronounced group structure of roll motions in the mode of parametric resonance (Tikka and Paulling, 1990) (Belenky et al. 2006).

The group structure makes several upcrossings at each semi-period very likely (Fig. 4). As a direct consequence of the pronounced group structure, the autocorrelation function of parametric roll dies out relatively slow (Fig. 5); so upcrossings become dependent on each other and the Poisson flow cannot be applied and the time between upcrossing does not follow an exponential distribution. Therefore assumption of the Poisson flow for the process upcrossing could only be applied for relatively large levels, which may not always be practical.
The calculations shown in Figures 2 and 3 use the data set from (Belenky 2004) that consisted from 50 records of 25 minutes each and described motion of post-panamax container carrier in head seas, speed 10 knots, significant wave height 4.2 m with modal wave period about 14 seconds.

The boundary was set for 15 degrees time between crossings, was processed and presented in a form of histogram (Fig. 6). The histogram was compared with exponential distribution (5) with the intensity calculated as an inverse value of the mean time between crossings. Test of goodness-of-fit was performed with chi-square method that turned out to be negative with zero value of probability of the difference caused by random reasons.

The histogram is clearly dominated by the first bucket (Fig. 6) describing very short duration between crossings; this may mean that upcrossings are happening on every period of motion (Fig. 4)

To avoid these limitations, the upcrossing theory can be applied to the envelope of the process (Fig. 7) rather than to the process itself. This makes roughly one upcrossing per group; and as groups tend to be longer as slower autocorrelation function dies out, the independence of the neighbor upcrossing is much more likely to be held even for smaller levels.

Histogram and distribution density for time between upcrossings based on envelope show a much better convergence (Fig. 8). Chi-square method yielded probability 45.3% (probability that difference between observed and theoretical distribution is caused by random reasons), so the distribution is likely to be exponential; therefore a hypothesis of Poisson flow has not been rejected.

The rate of upcrossing for the envelope can be expressed in the same way as for the process:

\[
\lambda = \int_0^\infty \alpha f(a = b, \dot{a}) \mathrm{d}a
\]

(6)

Where \( a \) is current value of the envelope (amplitude) and \( \dot{a} \) is its first derivative by time.

If the roll process is normal the envelope has a Rayleigh distribution:

\[
f(a) = \frac{a}{V_\phi} \exp\left(-\frac{a^2}{2V_\phi}\right)
\]

(7)

Here \( V_\phi \) is variance of roll motions.

The first derivative of the envelope of a normal process is distributed as follows (Belenky and Sevastianov 2003):

\[
f(\dot{a}) = \frac{1}{\sqrt{2\pi V_\phi (\omega_2 - \omega_1)^2}} \exp\left(-\frac{\dot{a}^2}{2V_\phi (\omega_2 - \omega_1)^2}\right)
\]

(8)

Here \( \omega_1 \) is a mean frequency of a spectrum:

\[
\omega_1 = \frac{1}{V_\phi} \int_0^\infty \alpha S(\alpha) \mathrm{d}\alpha
\]

(9)

\( \omega_2^2 \) is the second spectral moment:

\[
\omega_2^2 = \frac{1}{V_\phi} \int_0^\infty \alpha^2 S(\alpha) \mathrm{d}\alpha
\]

(10)

Parametric roll, however, is unlikely to have normal distribution (Belenky et al. 2003a), so distribution of amplitude and its first derivative require further study.

Alternatively, the rate of upcrossing can be found by direct calculations. However this way may require more computational resources.

Once the rate of upcrossing has been found probability of at least one upcrossing during time \( T \) can be expressed as:
To present the results of simulations in a form of a polar plot, time has to be set to, say, 6 hours, or a similar figure corresponding to the frequency of the weather forecast report.

Boundary $b$ is considered as an array of roll angle values – similar to currently employed ABS practice: 20, 30, 40 degrees, etc.

For each boundary $b_i$, the value rate of upcrossing can be calculated at each point of the polar plot identified with wave direction angle $\beta$ and speed $v$:

$$\lambda(b_i) = f(\beta, v)$$

These values actually represent a surface. If a plane is defined as:

$$\lambda_P = \frac{1}{T} \ln(1 - P)$$

The intersection of this surface with the plane yields a boundary: outside of the boundary are cases where probability of crossing of the angle $b_i$ at least once during agreed time $T$.

Probability here has to be considered as a sort of confidence probability; it is the matter of agreement as well as time $T$.

The main advantage of the scheme is that it allows creating the polar plot for specific time of observation without carrying out simulations for this time.

**Numerical Simulation: Green Water**

Green water represents an evident stability hazard for a jack-up in tow, because of very low freeboard, see Fig. 1 and 2. Numerical simulation of motion with influence of green water may be the future way of assessment stability of jack-ups in tow.

Currently, LAMP has a capability to simulate flow of water on deck including evaluation of the amount of water getting on deck when the deck edge is submerged, calculation of the flow characteristics of the water trapped on deck and decrease of the amount of the water due to outflow.

The solver for green water problem works in parallel with the main LAMP solver. The problem is invoked, when submergence of the deck edge is detected. Boundary conditions on the deck edge are known from main LAMP solver, so mass and velocities of incoming green water can be evaluated. A similar approach is used to simulate outflow of green water. Pressures caused by green water flow are evaluated on each time step; these pressures then are integrated over affected surfaces and resulting forces are included into integration of equations of motions. The new attitude of the ship on the next step and the new orientation of the deck, respectively, affect the flow of the green water, which is reflected in pressures and so forth.

There are several options in LAMP for green water: one, the most simple is based on hydrostatic and Froude-Krylov pressures only. Another option is based on shallow water calculation. The main assumption is that is as depth of the green water on deck is small in comparison with the length and width of the deck, the vertical gradient of fluid velocity can be neglected. This allows reducing 3D flow problem to 2D, respectively computational speed was increased.

Belenky et al. (2002, 2003) described application of LAMP with green water capability to access motions of a small fishing boat with a forecastle and low-freeboard main deck. Simulations were done both in calm waters and regular waves; results of simulations so strongly resembled observations done during the model tests that they could be considered as qualitative validation of green water capabilities of LAMP.

The feasibility study of application of LAMP for stability analysis of jack-up in tow was performed by ABS and SAIC. The study concluded that such application is possible. Modeling of the moon-pool in the middle of a jack-up platform has to be performed with caution and may require additional research.

Future success in application of numerical simulation for analysis of stability of jack-up in tow will constitute another example as to how a physics-based numerical simulation bridges the gap between approaches to stability of ships and offshore installations.

**Conclusions**

Appearance of a difference - the “gap” on how stability is evaluated and regulated for ships and offshore installations is related with historically distinct operational experience. The operation experience, so far, was the main focal point and background for existing stability standards.

With the development of technology, both ships and offshore installations become more and more specialized. At the same time, development of markets and technologies create novel designs that become increasingly different than their prototypes for which, significant operational experience is available.

As a result of these developments both, geometry of hulls and mode of operation are changing, invoking new physical mechanisms of stability failure. Parametric roll of large containerships could serve as an example of such non-conventional types of failure. Use of numerical simulation allows not only to predict likelihood of parametric roll, but also to develop an onboard guidance giving the crew valuable ship-specific information on parametric roll. Application of similar type of approach has a potential to evaluate danger of that green water poses for a jack-up in tow.

Therefore, further development in stability area will have to be based on understanding and modeling of physics of stability failures.

Numerical simulation of motions of ships and offshore installations provides a suitable environment for implementation of these models; however simpler analytical models still keep their place as a way to understand physics. Another aspect of the correct application of numerical simulation is to account for effect of structure damping, which would be of influence for buffeting and resonance issues.
simulations is rigorous probabilistic interpretation of the results. Formulation of some of the problems related to such interpretations was used in this paper as an example of such work.

Acknowledgement

LAMP has been developed by Science Application International Corporation (SAIC).
The development of the LAMP System has been supported by the U.S. Navy, the Defense Advanced Research Projects Agency (DARPA), the U.S. Coast Guard, the American Bureau of Shipping (ABS), and SAIC. The green-water development has been supported by the Office of Naval Research (ONR) under program manager Dr. Patrick Purcell, by the US Coast Guard under the Program manager Mr. Peter Minnick, and by ABS.

References