Orthogonal Tipping in Conventional Offshore Stability Evaluations

J. Andrew Breuer*
Chief Engineer Offshore Engineering Dep. ABS Americas
Karl-Gustav Sjölund
Consultant Researcher - Seasafe AB, Sweden

ABSTRACT

Orthogonal tipping is a phenomenon that frequently causes problems in the application of conventional stability evaluation methods when applied in all directions as is done for offshore structures. Experience shows that often it is difficult to find an interpretation of the stability rules that allows the calculation of a relevant free trim righting lever curve covering a sufficient range of heel. In the light of recent additions to the damage stability criteria for jack-ups introduced by ABS, the paper presents the nature of orthogonal tipping, the limitations of conventional stability analysis procedures, and an alternative method to evaluate the "Range of Stability" without explicit use of a righting lever curve. Although equivalent to the conventional methods based on the righting lever curve, this method avoids the orthogonal tipping problem, and thus consistently produces relevant results. The paper also investigates the possibilities to generalize the method to cover other types of stability criteria.

Keywords: *Offshore, Stability, mobile offshore unit, damage, range of stability*

1. INTRODUCTION

Because most offshore units and floating installations have comparable length and breadth, transverse stability is not sufficient to establish the safety of the floating vessel. This has been resolved by following conventional transverse stability methodology to any orientations. The methodology includes the development of righting arm curves with the hull rotating about an axis that is sequentially shifted at regular angular intervals for all 360 degrees.

The complexity brought in by incorporating a third dimension to the method can only be resolved with computers.

This approach applies to all offshore vessels; drilling units and offshore production installations. This includes jack-up and semisubmersible drilling units, drill ships, spar and semisubmersible production installations, and almost any vessel dedicated to the offshore oil industry.

2. HISTORY

Figure 1
Semi-submersible Drilling Rig

* The views expressed in this paper are those of the authors and do not necessarily reflect those of the American Bureau of Shipping or Seasafe, AB

While the offshore oil activities can be traced back to the early 1900's, drilling from a floating vessel was first achieved in 1947. Early mobile offshore drilling units (MODU) consisted of a deck barge with the industrial equipment set on deck. The first jack-up rig was commissioned 1954 and the first purpose built semi-submersible was built in 1964.

A group formed by regulators, naval architects, and rig designers took on the task of developing the first rules for MODU; the rules were first published in 1968 [1].

Figure 2
A four leg Jack-up drilling unit in operation

The Rules included many innovations; most notably the introductions of stability requirements; intact and damage.

The main reason for these innovations was the lack of statutory standards to resolve the unique proportions and subdivision of MODU.

While it is clear that conventional stability standards have little application to MODU, the methodology and approach to ship stability continues to influence the subject in the offshore industry.

3. METHODOLOGY

Stability analysis for offshore units is usually directed to the determination of the maximum allowable height of the center of Gravity (AVCG) as a function of draft.

The usual procedure is to calculate the AVCG based on the intact stability criteria and separately the AVCG based on damage stability criteria. The AVCG is presented to the onboard operating personnel either as a table or as graph. MODU are usually designed to operate in two different modes; normal operations and storm survival. While the intact stability criteria are the same, the former is based on a 36 $^{m}/_{s}$ wind and the latter on a 51 $^{m}/_{s}$ wind velocity.

Calculations are performed for a sequence of wind directions defined by the azimuth angle to establish the Rule requirement *to have sufficient stability (righting stability) to withstand the overturning moment equivalent to the one produced by a wind from any horizontal direction*[1].

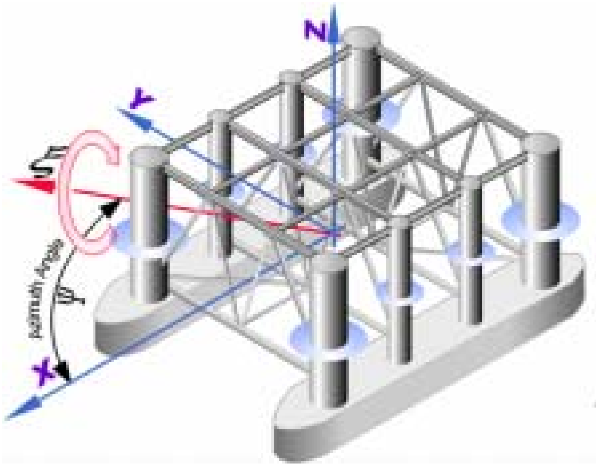

Figure 3
Axis system for stability evaluation of a MODU

For each azimuth angle Ψ, the righting arm (GZ) is calculated for a sequence of angles of inclination about the axis ξ. The axis coincides with heeling moment vector imparted by the wind.

As the hull heels around the axis, the center of buoyancy (CB) shifts in the direction of wind and in the direction perpendicular to the wind direction. Following the "free trim" standard, the perpendicular to the wind shift of the CB is neutralized by trimming the azimuth axis such that the center of gravity (CG) and CB remain on the same vertical Plane.

For the purpose of this paper, and following the common practice in industry, the following notation is used:

Generalized Heel (G-heel) is the angle of rotation of the hull about the Azimuth axis ξ. If the azimuth angle is nil, heel follows the definition used in shipbuilding.

Generalized Trim (G-trim) is the angle of the azimuth axis with respect to the horizontal. If the azimuth angle is nil, trim follows the definition used in shipbuilding.

Inclination is the angle between the hull base plane and the horizontal.

4. RECENT DEVELOPMENTS

In 1956 "QATAR I" became the first jack-up lost while in transit. Following that loss, not less than twenty-four other jack-up where lost in transit; last one in 1998.[2]

The investigation of these incidents resulted in many changes in the way these rigs are transported and operated. From a regulatory point of view, it was determined that most jack-up are well subdivided despite the lack of adequate subdivision standards.

The main weakness of most standards is the assumption that jack-up rigs are mainly exposed to damage by way of collision or from leakage through the bottom shell. This approach, that strongly emulates the earlier standards for conventional vessels, does not reflect the flooding through the deck that was determined to be the most frequent cause of loss of jack-up in transit.

Industry, gathered in various working groups, continued the research of the causes of these incidents. Based on the findings, new procedures for towing jack-up published in the early 1990's greatly reduced the frequency of these incidents. Another conclusion from this investigation established the need to develop adequate standards of internal subdivision of Jack-up. An-ad-hoc committee formed by representatives of Industry was reported in two papers presented at the International Conference in the jack-up platform [2], [3].

The main change brought in through the findings of the Ad-hoc committee is a new subdivision standard with the following notable aspects:

1. In addition to the compartments exposed to collision, all other compartments are subject to a single compartment flooding standard.
2. The pre-existing standard of positive stability and no down flooding under a 50-knot wind applies to all compartments regardless of location.
3. The unit after damage must have a residual stability with a minimum range of stability (RoS) of:

$RoS \geq 7^o + 1.5 \bullet \varphi_S$ or

$RoS \geq 10^o$ Whichever is greater.

Where φ_S is the static angle of heel after damage

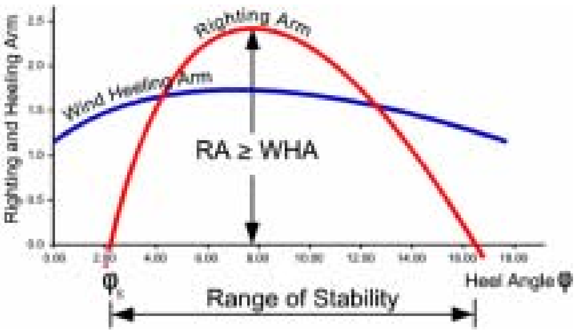

Figure 4
Residual stability standard for Jack-up

The new standard, published in 2005[4], applies to construction contracts signed after January 1, 2005. The new standard produced unexpected results when applied to on certain damaged conditions and direction of stability as a peculiar calculation phenomenon occurred. Even when the unexpected event was reported in 1986 by Van Santen [5], the problem caused much concern.

5. ORTHOGONAL TIPPING

The first indication of this calculation problem manifested when the GZ calculations failed to yield results for the full range of angles of inclination specified for the calculation run. When plotted, a typical GZ curve would look as in Figure 5.

Because offshore structures are irregular in shape, waterline properties used to balance the hull by way of multiple approximations do not conform to a continuous function. This lack of continuity is often the reason for failure to converge to a solution. Depending on the software, failure to converge sometimes results in an incomplete GZ curve such as those experienced when calculating stability curves to determine the RoS of damaged jack-up.

Figure 5 illustrates an incomplete curve. The termination of the curve will be referred as the “fading stability” point and the angle as FA

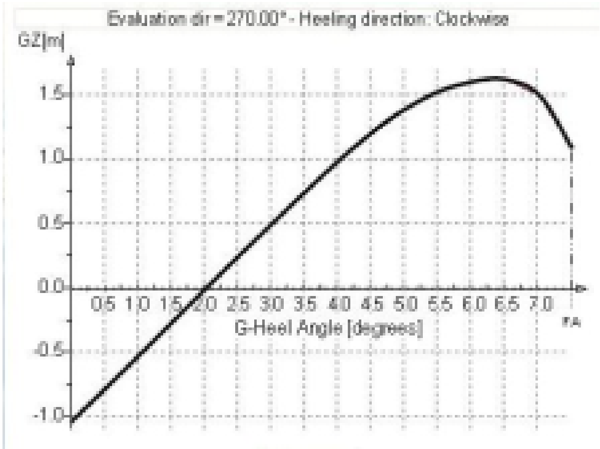

Figure 5
Incomplete GZ Curve

Further analysis of other results of the calculation, showed that the trim consistently grew to very large values as the hull was inclined towards FA. A first evaluation of this phenomenon interpreted as equivalent to a capsizing - not in the direction to which the unit was inclined but in the orthogonal direction.

The conventional RoS is established as a difference between the zero-crossing angles of the GZ curve as shown in Figure 2. However, a capsizing, regardless of direction, is equivalent to a zero-crossing and effectively the upper end of the RoS.

This conclusion, while plausible, lead to the unexpected and wrong conclusion that subdivision arrangements, and even well tested intact hull forms, where not adequate under the new criteria.

Questioning the adequacy of the conventional methods the investigation led to a return to first principles of engineering. This also involved the development of new computational tools for existing offshore stability software

6. ISO-ENERGY CONTOURS

6.1 Energy to heel and trim

The conventional approach to calculating the energy to heel the vessel consists in the integration of the righting arm moment frequently referred to as the “Area under the righting arm curve”

$$E_{P_{\Theta}} - E_{P_0} = \int_0^{\theta} GZ \cdot d\varphi \qquad (1)$$

This method is so generalized that most intact stability, and sometime damage stability, standards will express requirements of heeling energy in terms of Radian-meters or Foot-degrees as opposed correct ones in Length-force units.

The work needed to incline (further refer-

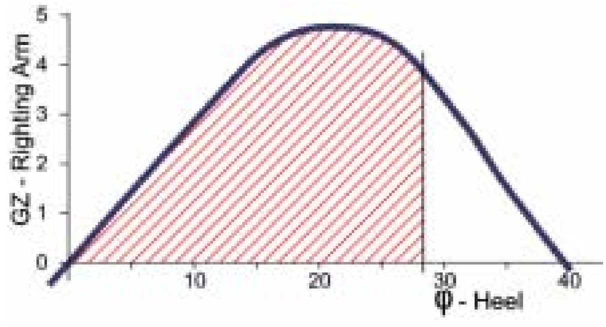

Figure 6
Conventional calculation of energy to heel

enced as energy to incline) corresponds to the increase in potential energy (E_P) and can be determined by rigorous method. This procedure requires an accurate determination of the position of CB. Manual calculations seldom meet this standard and the need for computers may explain why this methodology is rarely found in traditional text.

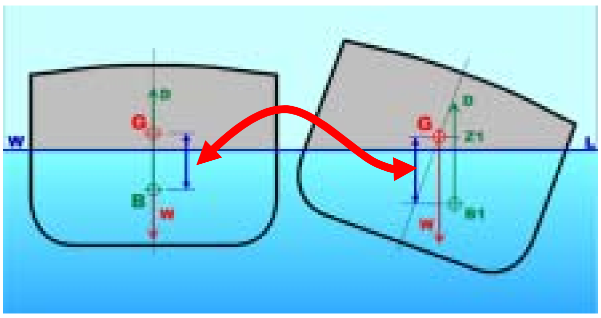

Figure 7
Rigorous determination of the energy to heel

For a constant displacement, the energy to incline is determined by the change in potential energy from the equilibrium position to the inclined position. The increase is proportional to the change in vertical distance between the center of gravity and the center of buoyancy.

Figure 7 illustrates the methodology and the E_P equation is:

$$\delta E_P = \Delta \cdot (B_1 Z_1 - BG) \qquad (2)$$

$$E_P \sim (B_1 Z_1 - BG) \qquad (3)$$

Where Δ is the displacement

The rigorous method to calculate the energy to incline compares the inclined-condition with the condition-of-equilibrium. Therefore, the calculation is independent of the path of integration and is not affected by the directions of stability, initial conditions, or the effectiveness of the iterative process to achieve balance.

6.2 Representing of the Energy to Incline

To visualize the energy we developed a model of a fictitious jack-up. A typical void compartment adjacent to the aft end of the hull is also flooded with direct communication with the sea.

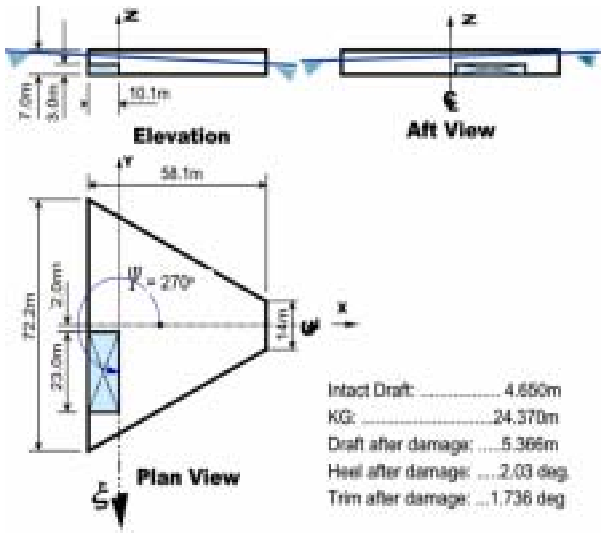

Figure 8
Model used for calculations and illustration

For the selected damage condition, with a constant position of the center of gravity and constant displacement, an azimuth of 270°, the energy to incline was calculated for a matrix of G-heel-G-trim combinations.

The calculated energy to incline, represented in an Orthogonal system of G-Heel (X axis), G-Trim (Y axis), and E_P (Z axis). The energy at the position of static equilibrium after damage (PSE) is used as the energy baseline.

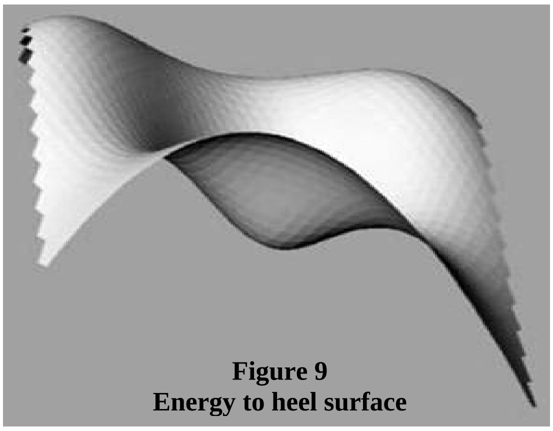

Figure 9
Energy to heel surface

In an orthogonal 3-axis system, the matrix of results of G-heel, G-trim, and Energy, represent a surface. The same surface can also be represented as a topographic chart by presenting E_P in terms of iso-energy contours. Having established the increase in vertical distance between the centers of Buoyancy and Gravity (BG), the analogy between the energy surface and the motions of a particle on a physical surface is evident and is used to understand statics of stability afloat.

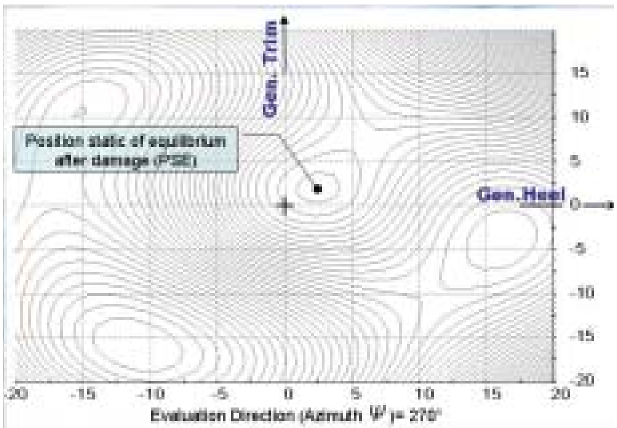

Figure 10
Iso-Energy contours

6.3 Nature of Orthogonal Tipping

To understand the subject event, the sequence of G-heel and G-trim calculated in the development of the GZ curve illustrated in Figure 5 is plotted in Figure 11. It can be seen that as the hull is G-heeled, the initial G-trim (2^o approximately) remains relatively constant but after 3 degrees of G-heel beyond the position of static equilibrium, G-trim increases to a point where the rotation is only in the "G-trim direction" with no increase of G-heel.

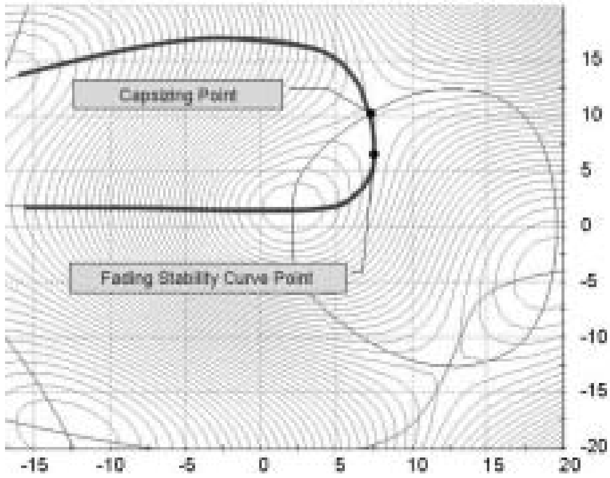

Figure 11
G-Heel - G-Trim path for GZ calculation

Because motions of the hull will not be toward an increased G-heel, the point of fading stability can also described as a point of refusal.

6.4 Observations on the Energy Surface

The general shape of the energy surface will change dramatically for each of the intact or damage cases and the parameters of the calculation. However, a number of notable points and lines is found on all surfaces.

Because the undisturbed hull will "balance" at the lowest point of energy achievable, the low point in a depression will always be the representation of a static position of equilibrium. If a surface is developed for a full range of G-heel and G-trim, more than one position of equilibrium will likely be found; usually corresponding to the upright and capsized conditions. Hulls with a CG below the CB, such as spars, submarines, drydock gates, will result in a single depression,

On conventional offshore hulls the general shape will have the depression with several "peaks" around them and the peaks will be connected by ridge lines

The ridge lines are notable in that are the slope "divide" and therefore constitute a "watershed". This means that a particle will roll down one side of the hill or the other, depending on which side of the watershed line it starts its motion.

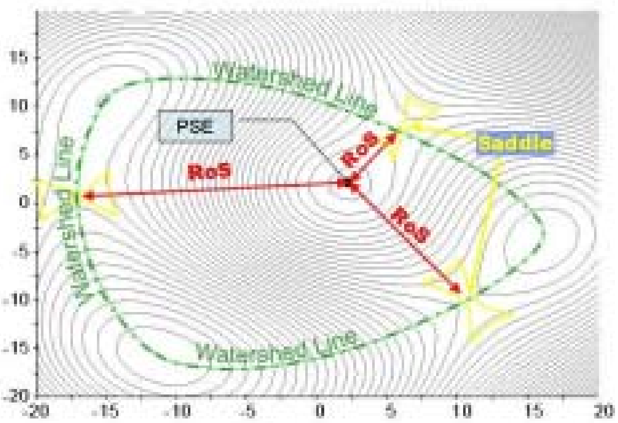

Figure 12
Notable points of the energy surface

Following the analogy of floating stability and particle motions on a surface, the watershed line is the limit of positive stability. A hull inclined beyond a combination of G-heel and G-trim will not return to the position of static equilibrium. Therefore, the watershed line corresponds to the second zero-crossing on the righting arm curve. Mathematically, if

$$E_P \sim \int_0^{\Theta} GZ \cdot d\varphi \qquad (4)$$

Then

$$GZ \sim \frac{\partial E_P}{\partial \varphi} \qquad (5)$$

Thus E_P will have a maximum value when $GZ = 0$.

The watershed line segment between peaks will have a "low point" or minimum. These saddle points are special points of capsizing as they are at relative low levels of energy. In the particular case shown in Figure 12, three saddle points are identified. The "distance" between the position of static equilibrium and each of the saddle points constitute a range of stability. Further, it is easy to establish that such distance is the minimum range for the family of righting arm curves calculated for that general direction.

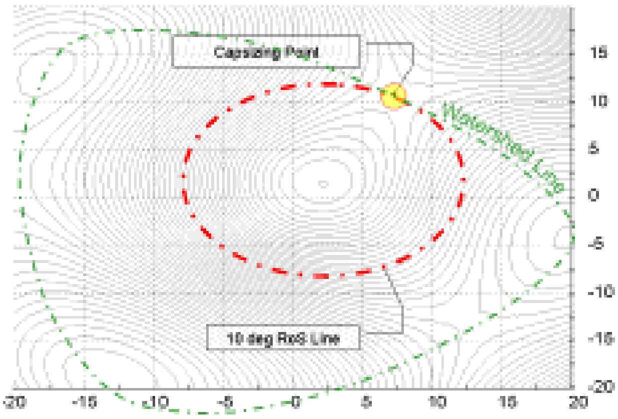

Figure 13
RoS on iso-energy contours

Going back to Figure 10 the GZ calculation showing the sequence of G-heel - G-trim combinations, it can be seen that the point of fading stability is reached before the point of capsizing. Because the latter point will not be reached by inclining the hull around the established axis, the concept of range of stability cannot be applied to the case.

The most important conclusion from this is that GZ curves that fade cannot be used to establish RoS.

6.5 Waterplane parameters in the Iso-energy contours

Assuming the hull fixed to the coordinate system, the waterplane may be described by the vector normal to the plane:

$$\overline{N} \bullet \overline{r} + d = 0 \qquad (6)$$

$$\begin{aligned}\overline{N} &= Sin\,\theta\,\hat{i} + \\ &+ (Cos\,\theta\,Sin\,\varphi)\,\hat{j} + \\ &+ (Cos\,\theta\,Cos\,\varphi)\,\hat{k}\end{aligned} \qquad (7)$$

Where:

$\overline{N}$: is the Plane's normal
$\overline{r}$: is a vector from the origin to any point in the plane

d: is the distance of the origin to the plane

θ: is the angle of G-Trim

φ is the angle of G-Heel

The angle Ψ from the axis of azimuth to the axis of inclination can be calculated as:

$$\psi = \begin{cases} \pi - ArcTan\,(N_1 / N_2) & if\ N_2 < 0 \\ -sign\,(N_1)\,\pi / 2 & if\ N_2 = 0 \\ -ArcTan\,(N_1 / N_2) & if\ N_2 > 0 \end{cases} \qquad (8)$$

or, for inclinations less than π/2 radians,

$$\psi = \begin{cases} \pi - ArcTan\,(Tan\,\theta / Sin\,\varphi) & if\ \varphi < 0 \\ -sign(\theta)\,\pi / 2 & if\ \varphi = 0 \\ -ArcTan\,(Tan\,\theta / Sin\,\varphi) & if\ \varphi > 0 \end{cases} \qquad (9)$$

The angle ψ' between the vessel's longitudinal axis and the axis of inclination is:

$$\psi' = \psi + \xi \qquad (10)$$

6.6 Range of Stability - Redefined

It is clear that determining RoS by developing a conventional righting arm curve is not adequate. Furthermore, the approach to evaluating stability by rotating the hull about a fixed axis is questioned.

If floating stability is defined as the ability of the hull to return to the position of equilibrium after it has been disturbed, we can define Range of Stability to be the angle to which the hull can be inclined and return to the position of equilibrium.

In accepting this premise, the "path" through which the hull returns, is not significant as long as it does not go beyond the boundaries of stable positions.

A further conclusion that drawn from this premise is that because the concept of rotation about a fixed axis is moot, we must accept that the range of stability is the difference between the inclination of the waterplane between the position of static equilibrium and the angle of capsizing.

To illustrate this point, Figure 13 shows the watershed lines and a line representing an inclination of 10^{o} beyond the angle of static equilibrium. RoS in the Iso-energy contours corresponds to the inclination of the hull at the position of static equilibrium and the closest point on the watershed line – most likely at the nearest saddle point

In Mathematical terms, RoS can be calculated as follows:

$$\overline{N_h} = -Sin\ \theta_h \hat{i} + (Cos\ \theta_h Sin\ \varphi_h)\,\hat{j} + (Cos\ \theta_h Cos\ \varphi_h)\,\hat{k} \qquad (11)$$

$$\overline{N_c} = -Sin\ \theta_c \hat{i} + (Cos\ \theta_c Sin\ \varphi_c)\,\hat{j} + (Cos\ \theta_c Cos\ \varphi_c)\,\hat{k} \qquad (12)$$

$$RoS = ArcCos\,(\overline{N}_h \bullet \overline{N}_c) \qquad (13)$$

$$RoS = ArcCos\,(Sin\,\theta_h Sin\,\theta_c + Cos\,\theta_h Cos\,\theta_c Cos\,(\varphi_c - \varphi_h)) \qquad (14)$$

7. ALTERNATIVE INCLINING PATH

7.1 Dynamic descent

Having established that the conventional approach to stability follows an unlikely sequence of heel-trim combinations, the question to resolve is which sequence is the theoretically correct path and what assumptions we must make to reach that answer.

Following the analogy of the particle moving on a surface, we could assume that a sphere in the position of static equilibrium, receives an impulse to roll uphill. Dismissing the effect of friction, we can expect the sphere to reach a certain elevation and then endlessly roll down and up the hill. With such motion, the sum of potential and kinetic energy remains constant. While special cases could result on an endless repeat of the same path, most likely, the sphere will roll following an apparently random path.

7.2 Steepest descent method.

The alternative to a dynamic approach is a quasi-static path. This means that as the particle returns to the position of equilibrium, the loss of potential energy does not convert to kinetic energy.

Under such a premise, the particle would follow the **steepest descent path** (SDP) such that the potential energy will deplete through the most efficient path. The path is a function of the starting point and the initial direction imparted to the particle.

If the floating stability evaluation case is assumed a static event, the SDP is a realistic solution; including the evaluation of RoS. Where dynamics are part of the event, the SDP departs from theory but follows first principles better than the conventional stability analysis.

The SDP has the simplicity needed to resolve stability expediently and it follows acceptable principles of physics. A dynamic approach, while possible, is extremely complex and still separated from reality due to the random nature of the environmental forces and excitations.

With the SDP approach, the starting point and the initial direction of motion determine the path. The path is perfectly reversible; meaning that the path does not depend on the direction of the motion, and that the path of energy buildup will be identical to the path of energy depletion.

If the vessel is displaced from its equilibrium to an arbitrary point somewhere within the "watershed" described, the moment resulting from the gravitational forces will always tend to rotate the vessel along a SDP. This is because the moment vector is always parallel to the SDP.

When the steepest descent method is used, we intrinsically allow the hull freedom to rotate relative the direction of the heeling and righting moments. This is the fundamental difference between the SDP method and the conventional free trim rotation that fixes the moment direction relative the ship geometry. The freedom to rotate prevents the occurrence of fading stability in SDP and the lack of it is the cause in the conventional approach

Figure 14 shows the families of paths that follow the SDP principle. We can note the following properties of the SDP:

1. All paths pass through the extreme points of the E_P surface - peaks and position of static equilibrium.
2. The path are perpendicular to the contour lines at the point of intersection.
3. Boundary lines between families of lines, a dividing line connecting the point of static equilibrium with the saddles, define the direction of minimum range of stability.

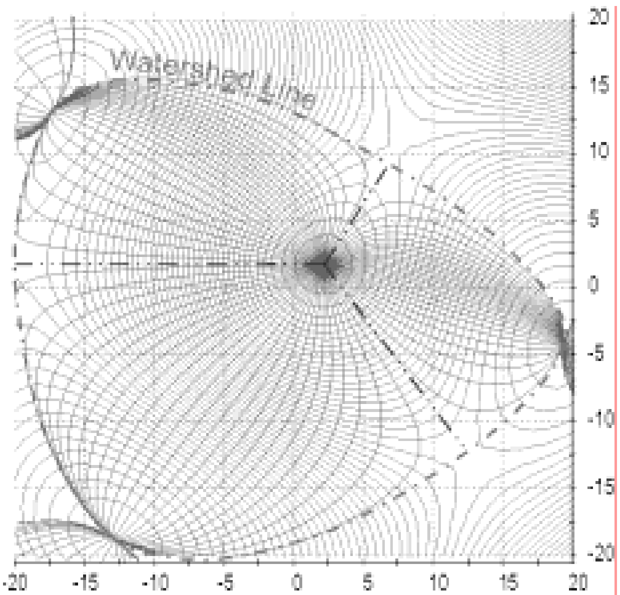

Figure 14
Steepest Descent Paths

4. The boundary lines are a singular case of a SDP but because the line reaches

the saddle, the hull capsizes without progressing on the watershed line.

5. There is no fixed relation between the moment direction and the inclination axis.
6. There is no fixed relation between the moment direction and a body-fixed axis.

7.3 Analysis of stability along a SDP

A Stability curve can be developed in association with any SDP under certain assumptions.

The GZ-curve is a function of one parameter ξ. For the steepest descent rotation path, the natural choice of ξ is the rotation along the SDP, i.e. a rotation that is parallel to the moment vector at all times. The value of ξ in a given point thus equals the length of the path measured from the point $\xi = 0$. This choice has the following two important advantages:

1. Only through this choice will the area below the GZ-curve be proportional to the buildup in energy. This is because the rotation is always parallel to the moment vector along the SDP.
2. It is always possible to present GZ as a function of ξ irrespective of how the path twists and turns, since the value of ξ always increases along the rotation path. Therefore, the GZ curve never fades, and orthogonal tipping does not occur. The curve allows evaluation of range of stability and other stability parameters.

A typical SDP Righting arm curve GZ = f(ξ) is illustrated in Figure 15.

As indicated before, the boundary line between families of SDP is a singular path that must be paid special attention. Because they terminate at the saddle point, a relative minimum E_P, this path is likely to be a critical one.

The SDP stability curve allows evaluation in the same way as a conventionally calculated stability. This includes the typical critical angles such as, first (ξ_1) and second intercepts (ξ_2), first (ξ_0) and second zero-crossing (ξ_c - static equilibrium and capsizing), and the angle of maximum righting arm (ξ_m). However, the concept of directionality, heel and trim is no longer relevant as the angle evaluated is the inclination of the hull and the concepts of heeling about an azimuth axis and the trimming of the axis are no longer valid.

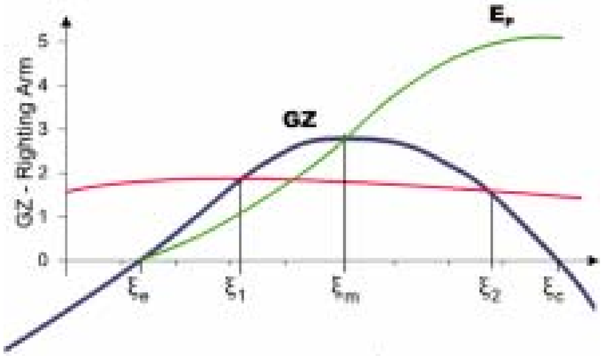

Figure 15
Steepest Descent Path Stability Curves

If the analysis assumes the superposition of a wind overturning moment, a relative rotation of the hull about a vertical axis must be accepted as the directionality of wind must be consistent with the rotation along the SDP.

7.4 Implementing the SDP concept

In principle, the evaluation of intact or damage stability based on the SDP method is not vastly different from evaluation based on free trim GZ-curves, but the notable difference in choice of rotation path(s) has a significant effect on the calculation algorithm. Obviously, there will be various solutions to the problem, and a detailed algorithm is outside the scope of this paper. However, for a vessel where no assumptions can be made regarding critical evaluation directions, the procedure could involve the following steps:

1. Analyze the function Ep to find any extreme points within a relevant definition region, e.g. all inclinations < 40 degrees. Since the components of the moment vector M are the partial derivatives of Ep, the most straightforward approach is to find all solutions to the equation $\mathbf{M} = \mathbf{0}$ within

the definition range. The functions Ep and **M** can be approximated using a grid of triangular facets. Each value point in the grid corresponds to a certain heel and trim and the buoyancy and displacement need to be balanced for each knot in this grid.

2. Determine the rotation paths. In sectors of the definition region where the watershed line occurs, each path will pass through either a saddle-point or a local maximum (See figure 14). The paths must be distributed in such a way that they cover the entire definition region in order to ensure that critical case will be identified during the criteria evaluation. Care should be taken to include the singular paths that pass the saddle points.
3. Generate the stability curve corresponding to each path. These curve plots the magnitude of M (divided by the displacement) as a function of ξ, the rotation along the SDP (See section 7.3).
4. For each of the stability curves, verify a set of criteria.
5. If the task is to establish a limiting KG, steps 1-4 need to be repeated to arrive at the limiting value. One possibility is to vary KG using bisection. The balancing of buoyancy and displacement is performed only once, and need not be repeated in this iteration.

8. CONCLUSIONS

Experience shows frequent problems to establish Free-Trim GZ-curves for different types of offshore units. This makes stability evaluation problematic. The evaluation of ABS' new damage stability standards depending on the Range of Stability (RoS) is significantly affected by this problem.

Conventional free to trim stability procedures are inadequate to establish Range of Stability because it assumes an unrealistic sequence of heel-trim combination.

Conventionally obtained righting arm curves in offshore can terminate at unexpected angles of heel. The fading of these curves is not an indication of capsizing and do not constitute a second zero-crossing of the GZ curve. If conventional methods are applied, fading GZ curves should be disregarded.

The energy to incline a hull is a function of the initial and final position of the hull and not a function of the sequence of heel trim combinations.

Range of stability and other stability properties can be determined by analysis of the energy to incline surface.

Applying the steepest descent path to the evaluation of intact and damage stability appears to be more rational that the conventional free to trim.

The steepest Descent Path allows the rotation of the azimuth axis and resolves the problem of orthogonal tipping.

9. ACKNOWLEDMENTS

The authors wish to acknowledge the unrelenting support of the ABS Americas Offshore Stability Team, including, T.S. Bush, R. dos Santos, B. Radanovic, and J.H. Rousseau

10. REFERENCES

[1]ABS Rules for Building and Classing Offshore Mobile Drilling Units, 1968 (section 3.13.2, Stability Afloat,

2 Breuer, J.A., Bowie, R., 2003, "The Future of Jack-up Stability Learning from Our Past", Ninth International Conference on the Jack-up Platform, City University, September 2003

[3] Breuer, J.A., Bowie, R., Bowes, J., "Internal Subdivision of Jack-ups- a new standard to resolve an old concern", Tenth International Conference on the

Jack-up Platform, City University, September 2005

[4] ABS Rules for Building and Classing Mobile Offshore Drilling Units, 2005

[5] Joost van Santen, "Stability calculations for jack-ups and semi-submersibles", Conference on Computer Aided Design, Manufacture and Operation in the Marine and Offshore Industries, September 1986