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IMPACT OF LINEARIZATION OF BILGE KEEL DAMPING ON THE EARLY ASSESSMENT OF VESSEL OPERABILITY

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ABSTRACT

This paper investigates the benefits of a method whereby roll damping is assessed for each sea state in a given scatter diagram. Particular emphasis is given to the quadratic damping induced by the vessel bilge keels. For each sea state in a scatter diagram, an iterative process is used to obtain a sea state dependent linearized bilge keel damping. This paper shows the impact of such a refined method on the evaluation of operability for a generic vessel. It also provides a comparison with simpler operability assessment methodology both in terms of overall vessel operability and limiting operational sea states for typical scatter diagrams and operability criteria.

INTRODUCTION

Proper assessment of vessels operability - i.e. the percentage of time vessel motions or accelerations remain below a set of allowables in a given geographical area - is of great interest to operators and designers alike. To operators, operability is an indication of future cash flow and can help in the investment decision. To designers, operability indicates the fitness for purpose of the vessel.

Of all ship motions, roll is of particular importance in the determination of operability for two main reasons:

1. Roll motions can become very important in certain sea states preventing normal work operations.
2. Roll motions are inherently non-linear and dominated by viscous effects which renders their assessment particularly difficult at an early design stage.

Commonly used techniques for early assessment of a vessel operability relies on simple assumptions regarding roll damping. Typically, roll damping is introduced in the equation of motion as a constant value of linear damping obtained by either model testing or semi empirical methods such as described by Ikeda-Himeno ([1]) or via design experience. This unique value is usually determined for a limiting operational sea state which is imposed as a design case. It is then used during the operability assessment to derive both the actual limiting sea state and the overall operability of the vessel.

Introducing a sea state-dependent roll damping, calculated automatically for all sea states, provides better estimates of roll motions and resulting accelerations. It can therefore lead to a more accurate operability assessment.

OPERABILITY CALCULATION

Contour of limiting sea states

It is possible to calculate the response of a structure for a series of sea states defined as an Hs-Tz scatter diagram. If a criterion on any relevant seakeeping quantity (motion, accelerations, probability of extreme events etc) is defined, a contour of limiting sea states for this criterion can be deduced. Such a contour already provides valuable information independently of the probability associated with a given sea state which is taken into account in the calculation of the operability index.

Operability Index

In this study we define the operability index as the percentage of time a vessel can carry-out normal working operations. Thus the operability index of a vessel provides an indication of the vessel uptime in a given area of the world. It also provides a way to compare different designs, and thus evaluate which design can generate higher returns.

To compute the operability index, knowledge of the following is essential:

1. vessel motion characteristics,
2. a set of operability criteria,
3. a set of environmental conditions.

Indeed the index is computed by evaluating vessel motions against a set of criteria, for all sea states in a scatter diagram.

If the vessel heading is fixed, such as for a pipelay vessel, the operability index corresponds to the average operability over all wave directions with equal weight given to all directions.

If on the other hand, the vessel is free to weather-vane (i.e. free to head into the waves), such as a dynamically positioned drillship, the operability index corresponds to the average operability over a limited set of directions: typically waves from +-30 degree off the bow.

Using this information it is possible to assess the percentage of the time a vessel is able to perform in a given region of the world.

Operability criteria

Several operability criteria can be used to assess a design, see [2] and [3]. In this study two sets of criteria are used separately to illustrate the impact of the method on an operability index calculation.

The first set of criteria is typical of drillships and corresponds to motion limitations imposed by the moonpool configuration (limited roll angle) and the riser telescopic joint (limited heave). The second set of criteria corresponds to the Nordforsk criteria for accelerations and roll for light manual work. While the first set of operability criteria relates to equipment limitations, the second set is more related to human factors. The details of both sets are given in Table 1.

Table 1 – Operability criteria

Set	Criteria	Value
1 - Equipment-related limitations	RMS roll	4.0 [deg]
	RMS heave	4.0 [m]
2 - Nordforsk light manual work (human related)	RMS vertical accelerations	0.15g [m/s^2]
	RMS lateral accelerations	0.10g [m/s^2]
	RMS roll	6.0 [deg]

For the Norforsk criteria, accelerations are calculated at the locations given in Table 2. In this table, coordinates are given with respect to the aft perpendicular, the centerline and the base line.

Table 2 – Position of points for accelerations

Points	Location
1-Bridge	[196; 0; 39]
2-Aft Perpendicular	[0; 0; 21]
3-Working Area	[104; 0; 35.5]

Environmental conditions

As already mentioned, a vessel operability index is always associated to a specific environmental condition.

The goal of this study is to assess the impact of using sea state-dependent roll damping on the operability index. Therefore two different scatter diagrams are used which correspond to areas 4 and 32 of the global waves statistics [4]. These areas are shown on Figure 1.

Area 4 corresponds to the Norwegian Seas. It is characterized by a significant number of high sea states and is usually considered a harsh environment for operations.

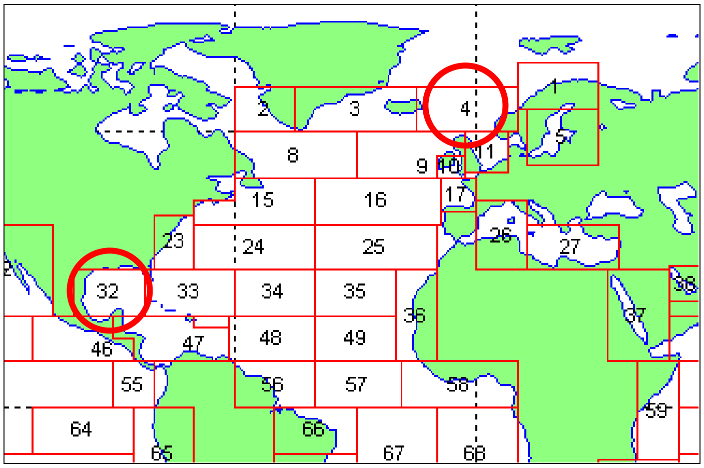

Figure 1 – Norwegian Seas (Area 4) and Gulf of Mexico (Area 32) of the Global Waves Statistics

Area 32 corresponds to the Gulf of Mexico. This region is characterized by lower extreme sea states (with the exception of hurricanes which are not considered in this study) and is much milder than the Norwegian Seas.

For both scatter, the JONSWAP spectrum is used. The relationship between (Hs, Tz) and (γ, Tp) is determined using the formulation presented in DNV-RP-C205 [5].

THEORY

Assumptions

A frequency domain analysis is used to calculate RAOs of ship motions. Assumptions of the frequency domain approach are:

- linearity,
- small motions and small wave slope,
- ideal fluid (potential flow theory),
- no effect of mooring, current, drift or wind forces.

The model chosen corresponds to a drilling vessel in operations without forward speed.

Vessel motion characteristics

The 3D diffraction-radiation software AQWA is used to compute the hydrostatic and hydrodynamic properties of a vessel. These properties can in turn be processed to compute the response amplitude operators (RAOs) of each vessel motion. For roll motion this computation takes into account an additional amount of roll damping, which can be either constant or sea state and direction dependent.

The knowledge of the vessel RAOs is sufficient to compute the significant motions in any given sea state.

Ship response in an irregular seaway

The radiation-diffraction analysis provides the hydrodynamic coefficients and excitation forces from which the equation of motion can be solved yielding the response amplitude operators (RAOs) per unit wave height for the six degree of freedom.

The wave spectrum used in the present calculations is a standard JONSWAP spectrum defined in terms of significant wave height, peak period and peakedness factor [5] .

$$S_w(\omega) = \frac{5}{16} H_s^2 \omega_p^4 \omega^{-5} \exp\left\{\frac{-5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right\} \cdot A_\gamma \cdot \gamma^{\exp\left\{-0.5\left(\frac{\omega-\omega_p}{\sigma\cdot\omega_p}\right)^2\right\}} \quad (1)$$

With:

- Hs = significant wave height,
- ω_p = peak frequency,
- γ = non-dimensional peak-shape parameter ,
- σ = spectral width parameter such that σ= 0.07 for $\omega < \omega_p$ and σ= 0.09 for $\omega > \omega_p$,
- $A(\gamma) = 1-0.287 \ln(\gamma)$, a normalizing factor.

Setting Gamma to one gives the standard Pierson-Moskowitz spectrum for fully developed seas.

For each degree of freedom, the response spectrum Sr(ω) is derived by processing the wave spectrum Sw(ω) through the Response Amplitude Operators H(ω):

$$S_r(\omega) = S_w(\omega) H^2(\omega) \quad (2)$$

The linearity assumption allows deriving the response in irregular waves as the summation of response in regular waves. For ships, this assumption is practically valid for all motion except roll. Indeed, the amplitude of roll at resonance is a function of the roll damping, which, for conventional ship hull form, is very small. Therefore another source of damping becomes predominant. This additional damping is the viscous damping generated essentially by friction, eddy making at bilge and bilge keels damping. Himeno ([1]) gives a detailed breakdown and estimation of the viscous damping components. The viscous damping depends on the roll velocity and is therefore non-linear.

Roll damping linearization

In order to use frequency domain analysis for motion prediction, it is necessary to linearize the viscous roll damping. This is done by adding to the linear damping term of the equation of motions a damping coefficient that represent the energy dissipated through viscous effects. Several techniques are commonly used to linearize the damping: experimental determination of linear and non linear roll damping from decay model tests, semi-empirical Ikeda method ([1]), harmonic linearization or stochastic linearization.

The stochastic linearization was implemented for our study as it is judged to be the most physically relevant technique for irregular seas. This method aims at minimizing the least-squares error between the non-linear damping and its linear approximation in a sea state. Its interest and limits are discussed thoroughly by Wolfram [6].

The non linear damping moment of the equation of motion can be expressed and linearized as shown hereafter:

$$M = B_{rad}\,\dot{\varphi} + B_q\,\dot{\varphi}\left|\dot{\varphi}\right| = (B_{rad} + B_{qlin})\,\dot{\varphi} \quad (3)$$

$$B_{qlin} = \sqrt{\frac{8}{\pi}} B_q \sigma_{\dot{\varphi}} \quad (4)$$

With $\sigma_{\dot{\varphi}} = \sigma_{\varphi} \times \frac{2\pi}{Tz}$ and $B_q = f(\Delta, L_{PP}, B, T, L_{BK}, H_{BK})$

And with:

- σ_{φ}= rms of the roll angle

- $\sigma_{\dot{\phi}}$ = rms of roll velocity
- T_Z = zero up-crossing roll period
- B_{rad} = potential radiation damping [kg.m^2/rad/s]
- B_q = quadratic damping [kg.m^2/rad]
- B_{qlin} = linearized quadratic damping [kg.m^2/rad/s]
- L_{BK} = Bilge keel length
- H_{BK} = Bilge keel height

The quadratic damping Bq may then be estimated from model test results. In-house regression analysis of roll model test results of similar vessels shows that this quadratic damping can be non-dimensionalized based on the bilge keel sizes and ship dimension. This formulation is used in this paper for its ability to reflect the dominating effects of the ship displacement and dimensions and the length and width of the bilge keels which are the leading parameters for the determination of the quadratic damping.

As can be seen in Equation 4, the quadratic damping is linearized using the variance of the roll velocity itself derived from the variance of the roll motion. The variance of the roll motion is calculated by integration of the roll response spectrum calculated according to Equation 2. An iteration method is used to obtain a convergence on the roll velocity. Typically this convergence requires 10 iterations to achieve a sufficient accuracy on the roll velocity.

For a given sea state, the roll damping is linearized for each heading. Then the process is repeated for each sea state of a scatter diagram.

RESULTS

General overview

This section provides an overview of the results obtained using the roll damping linearization technique described in the previous section. The first results presented show the effect of the stochastic linearization of the roll damping on the roll rms and its impact on an operability index based on a single criterion for the roll rms. Secondly, operability index based on the Nordforsk criteria with constant and linearized roll damping are shown and discussed. Finally, a sensitivity study is performed to evaluate the impact of the bilge keel length on the operability index.

The calculations are carried-out using a generic deep water drillship. Even though this vessel is a drillship, we consider both the weather-vaning and fixed heading cases for the operability calculation. In this paper, weather-vaning refers to wave directions limited to +- 30 degrees from the bow: the vessel is heading into the waves.

Basis of comparison

Vessel data

For the calculations, a generic hull with the particulars mentioned in Table 3 is used. Table 4 gives the vessel motion natural periods as calculated using its hydrodynamics properties.

Table 3 – Vessel particulars

Parameter	Value	Unit
Displacement	62261	[t]
L_{pp}	210.1	[m]
Beam	36.00	[m]
Draught	10.06	[m]
GM	5.93	[m]
K_{xx}	0.44 B	[m]
K_{yy}	0.27 L_{pp}	[m]
K_{zz}	0.27 L_{pp}	[m]
Bilge keel length	0.5 L_{pp}	[m]
Bilge keel height	0.02 B	[m]

Table 4 – Vessel natural periods

Motion	Natural Period [s]
Heave	8.95
Roll	14.30
Pitch	8.50

Benchmarking data

To show the impact of sea state-dependent roll damping on the operability index, a reference roll RAO with constant damping is used for the computation of a reference operability index.

Figure 2 shows the reference roll RAO used for benchmarking. This roll RAO has a total amount of damping equal to 4% of the critical damping value. This amount of damping corresponds to a typical operational sea state.

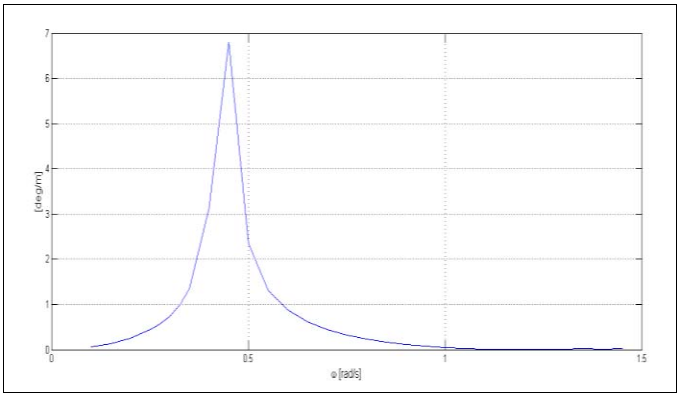

Figure 2 – Roll RAO with 4% Critical damping in beam seas

Sea state-dependent roll damping

Figure 3 shows the variation of linearized roll damping as a function of wave height Hs, in beam seas. It also shows the roll rms obtained with both methods. Each sea state is modeled as a JONSWAP spectrum with a peak period $T_P = 14$ s, and a peakedness parameter $\gamma = 3.3$.With a constant damping, the rms of roll grows linearly with the wave height as expected under the assumption of linearity. When the stochastic linearized damping reaches the value of 4%, the rms of roll is identical in both cases. For low sea states "real" damping is less than the constant value of 4%. This implies that for such sea states roll motions are under-predicted using constant damping. The reverse is true for higher sea states. With increasing wave height, the error on the roll prediction increases dramatically. This justifies the need for a sea state-dependent linearized roll damping. A difference of 50% is achieved in this case for Hs=6m.

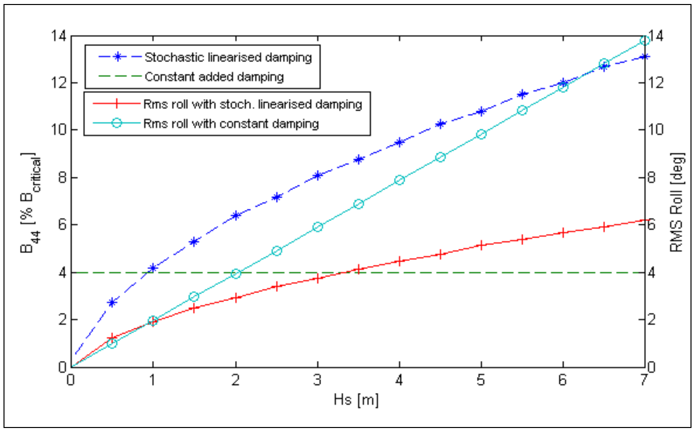

Figure 3 – Percentage of critical roll damping and roll RMS vs. Hs – Left scale shows the percentage of critical roll damping – Right scale show the roll RMS.

Figure 4 presents a map of the linearized roll damping as a function of Hs and Tz. This can be seen as an extension in three dimensions of Figure 3 illustrating the effect of the peak period of the spectrum with respect to the ship natural period.

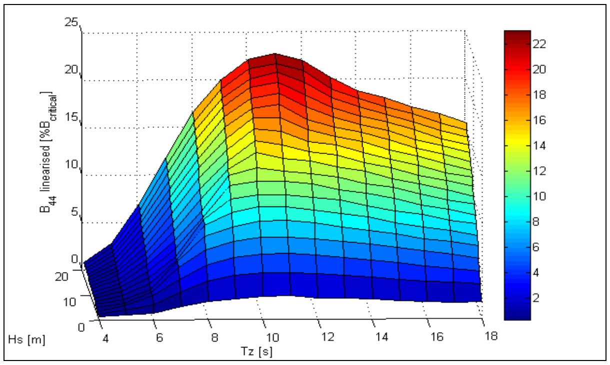

Figure 4 – Map of linearized roll damping – Notice the bulge around the vessel natural roll period (Tz ~ 12s).

Operability index

Single criterion index

To illustrate the impact of sea state-dependent roll damping on the operability assessment, comparative calculations are performed for two different scatter diagrams, Zone 4 and Zone 32, see Figure 5 and Figure 6. The criterion used is the limit on the roll rms of 4 degrees. Table 5 shows the results obtained for this single criterion. The number between brackets corresponds to the operability index when the ship is weather-vaning.

Table 5 – Single criterion operability indices

	Zone 4	Zone 32
Constant	89% (99%$_{WV}$)	96% (100%$_{WV}$)
Sea state dependent	97% (100%$_{WV}$)	98% (100%$_{WV}$)

Two comments can be made regarding those results. First, the differences in operability index are more important for the Norwegian Seas scatter. This can be explained by looking at the sea state distribution and the relative position of the limiting sea state curves for roll rms (see Figure 6). For a vessel with a lower roll natural period, the differences in operability between constant and sea state-dependent damping would be more important: the contours would include more sea states. For this vessel, the difference in operability calculated using the single roll criterion is about 8%, or a calendar month, for the Norwegian Seas. Second, differences in the case of weather-vaning are minimal (1% or less). This of course is not surprising: for a weather-vaning ship, roll motions are more limited.

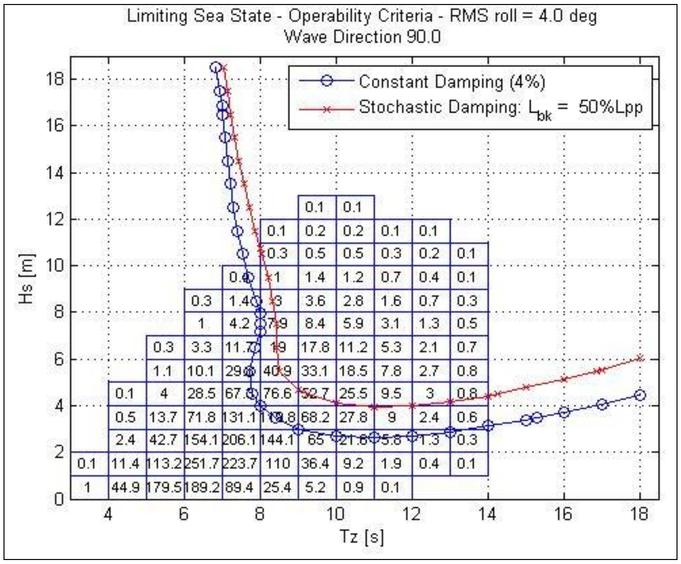

Figure 5 – Limiting sea state contours based on roll rms criterion for beam seas. The contour is plotted over the 1 year scatter diagram for Zone 4.

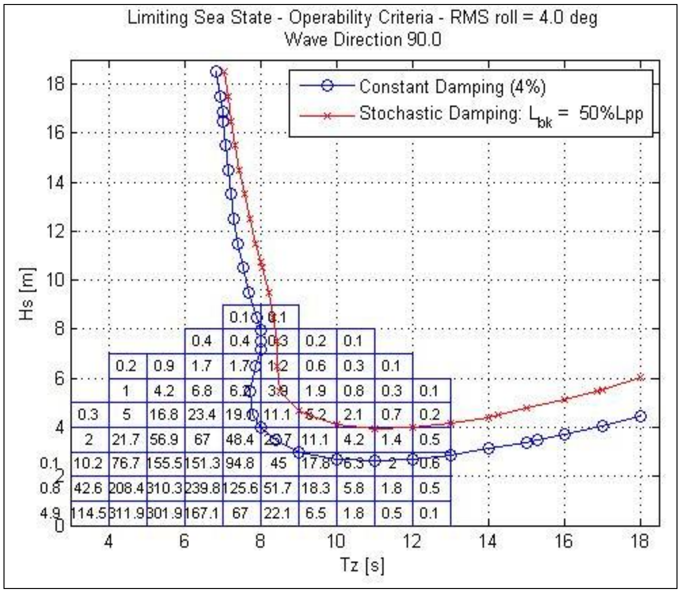

Figure 6 – Limiting sea state contours based on roll rms criterion for beam seas. The contour is plotted over the 1 year scatter diagram for Zone 32.

Index based on multiple criteria

For this comparison both criteria sets presented in Table 1 are used to see the impact of the roll damping linearization on an index based on multiple criteria. Operability indices using these criteria with and without stochastic linearization are presented in Table 6.

Table 6 – Operability indices based on multiple criteria

	Zone 4	Zone 32
Constant	84% (97%$_{WV}$)	96% (100%$_{WV}$)
Sea state dependent	87% (98%$_{WV}$)	97% (100%$_{WV}$)

Little differences in the operability index can be seen between constant and sea state-dependent damping. Contours of the limiting criteria in beam seas are presented in Figure 7 for the different points of Table 2. It is clear from these plots that the lateral accelerations are governing for the operability of this vessel in beam seas as the contour of accelerations at 0.1g is well below the contours of other criteria for all points. Note that the vessel heave and roll contours are independent of the point considered (they correspond to the motions at the center of gravity).

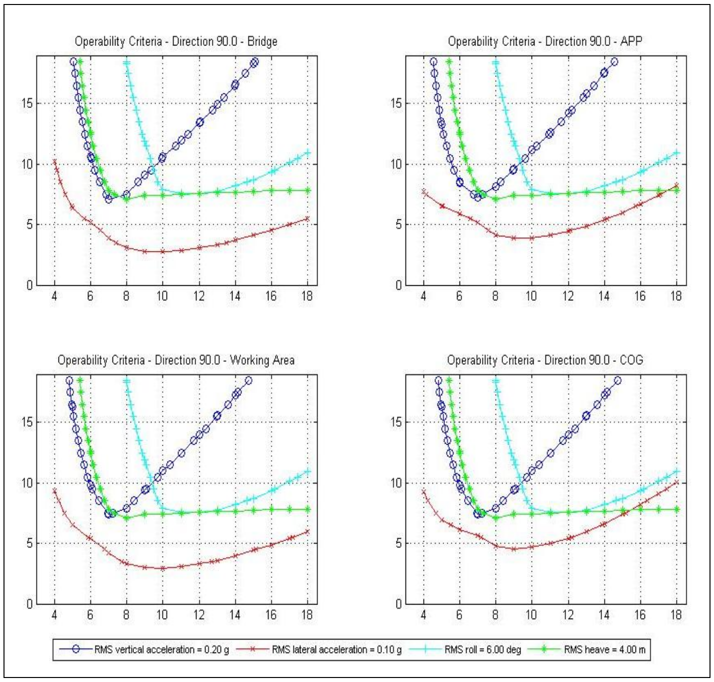

Figure 7 – Limiting sea states calculated using the Nordforsk criteria for a series of (Hs, Tz) and at different locations. Plots are for beam seas.

Figure 8 shows the contours of lateral accelerations with and without damping linearization. The proximity of the two curves shows no significant improvement compared to the use of a constant damping. It was expected that by improving the roll prediction, a similar improvement would be obtained with respect to the criteria for lateral accelerations. In fact the lateral accelerations decrease as a result of increased roll damping in the same proportion as the roll motion. However, the level of the criteria for lateral accelerations is such that in our case the contours of accelerations with and without linearized damping remain very close.

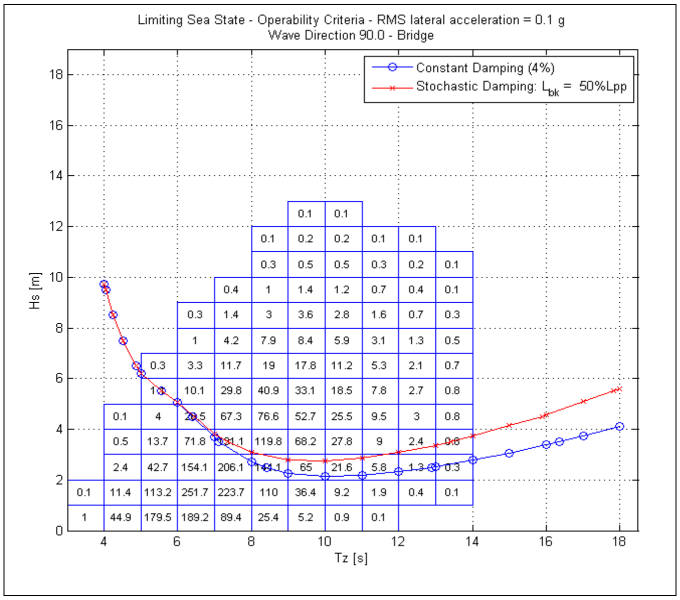

Figure 8 – Limiting sea states contours of lateral accelerations at the bridge in beam seas with (red) and without (blue) linearized damping

A plot of the lateral accelerations at bridge as a function of Hs, and for T_P = 14 s, is presented in Figure 9. It shows that for the case studied here the criteria of 0.1g is so small as to induce no significant improvements compared to the 4% constant damping case (0.5m in significant Hs at the natural period). It also means that for the chosen set of bilge keels, a constant value of 4% of critical damping is a good estimate for lateral accelerations around 0.1g.

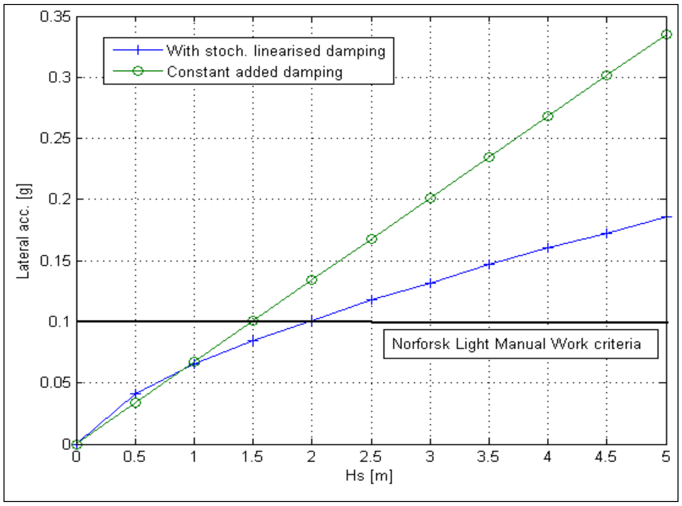

Figure 9 – Rms of lateral accelerations vs. Hs for beam seas. Notice the small difference in Hs (0.5m) between constant and sea state-dependent roll damping for the 0.1g threshold.

Sensitivity to bilge keel length

The formulation of the quadratic damping used in this paper depends on the bilge keel dimensions. To assess the impact of those dimensions on the ship operability, a sensitivity analysis is performed on the bilge keel length. Bilge keel length of 40%, 50% and 70% of Lpp are considered. Table 7 shows the final operability indices for three bilge keel lengths in the Norwegian Seas area (zone 4).

Table 7 – Single criterion operability indices for three bilge keel length

	0.4Lpp	**0.5Lpp**	**0.7Lpp**
Constant damping	89%	89%	89%
Stoch. linearized damping	95%	97%	98%

The influence of bilge keel length on the operability index is limited. However, as can be seen on Figure 10 the impact on roll motions is more important. At Tz = 10s, the significant wave height for which a roll rms of 4 degrees is reached is respectively 3.5, 4 and 5 meters. The limited impact on the operability index is once more the consequence of a high roll natural period.

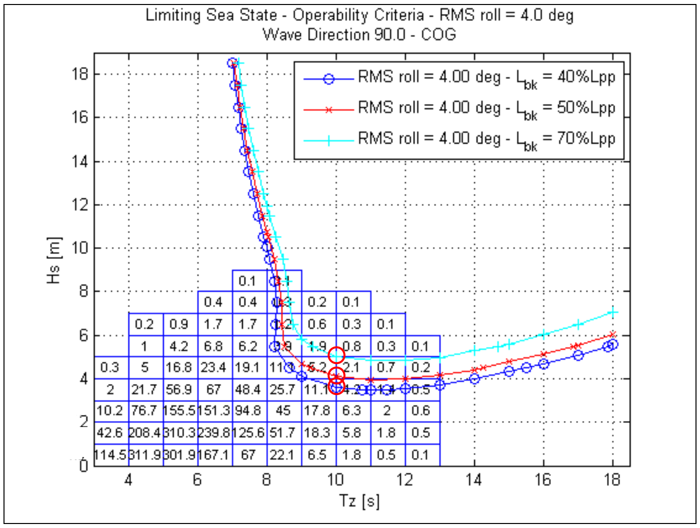

Figure 10 – Limiting sea states contours of rms roll in beam seas with linearized damping for three keel length. Red circles show the limiting wave height at Tz = 10s

CONCLUSIONS

The roll damping is systematically linearized with the stochastic method. In this method, a company-based model test database is used to derive a value of the quadratic damping. Through the process of linearization, the amount of roll damping becomes sea state and direction dependent. This process results in a more accurate prediction of the roll and lateral acceleration compared to the use of a constant added linear damping.

The effect of this method on operability indices is assessed for the Norwegian Seas and Golf of Mexico areas. Based on a single criterion on roll motion the operability index improves significantly. For multiple criteria, the differences are only marginal for this vessel. In this case the lateral acceleration at bridge is the governing criterion. In general the impact on the operability index is strongly dependent on the number of sea states around the vessel natural roll period.

A sensitivity study on the bilge keel length confirms the efficiency of bilge keels in reducing roll motions. It further demonstrates the interest of the method for the early assessment of bilge keel size.

The advantage of this method goes beyond operability assessment. It can be used in the following analysis:

1. Evaluation of extreme roll motions and lateral accelerations for survival sea states.
2. Application to all types of vessels with different motion and limitation characteristics.
3. With further data on the quadratic damping the method can be extended to cover non-conventional hull forms.

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