Probabilistic Analysis and Design in Relation to Riser-Riser Collision

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ABSTRACT

For design of deep-water riser arrays, consideration must made of the possibility for mechanical contact between the different riser pipes. Both the anticipated frequency of collision and the resulting stresses in the pipes needs to be estimated. Such an assessment need to cover a certain range of conditions regarding environmental loading and surface floater motions. The present paper outlines a procedure which allows the most "critical" conditions to be identified based on an iterative approach. For each "load case", which corresponds to a certain combination of environmental actions and surface floater motion, the corresponding probability distribution of contact stresses is computed.. Furthermore, the accumulated damage for each load case (referred to a certain duration) is estimated.

The numerical procedure for external load calculation is based on Computational Fluid Dynamics (CFD). For a given riser spacing, interpolation is performed during the response simulation in a pre-established data base. Contact between pipes is checked at each time step by looping through the nodal coordinates of the Finite Element Mesh which represents the pipe geometry.

By assembling the response and accumulated damage which correspond to all the different load cases, the long-term probability distributions and weighted damage are calculated. Relevant extreme response levels with given return periods and the total accumulated damage for a given duration are subsequently estimated. The procedure is applied to a particular example riser configuration.

KEYWORDS: Riser collision; stress; fatigue; probabilistic; design.

INTRODUCTION

The collision frequency for pipes within a riser array is influenced both by the current magnitude and its depth variation. In addition, top end motions may have strong effects. The probabilistic combination of current magnitude and amplitude of surface floater motion is accordingly identified as a highly important issue in the present context. Furthermore, the interaction between current velocity and top end motion in relation to collision frequencies and stresses is generally of a highly nonlinear character.

The joint modeling of current and floater motion is presently based on their respective long-term distribution functions. The primary response quantity is presently taken to be the pipe stresses associated with each collision. It is illustrated how the design value for the stress (with a specified return period) can be obtained based on the input distributions. The response analysis is performed in the time domain. The current is presently modeled in terms of a given (planar) profile which is scaled by the surface magnitude.

Calculation of hydrodynamic forces is based on results obtained by Computational Fluid Dynamics (CFD). These results are stored in a data base on non-dimensional form. Force parameters are subsequently evaluated by interpolation in this pre-established data base during the response simulation. Contact between pipes is checked at each time step by looping through the nodal coordinates of the Finite Element Mesh which represents the pipe geometry.

Within the framework of state-of- the-art methods for numerical response calculations, application of a fixed amplitude for the surface floater motion is presently considered to be adequate. However, as the computational tools become more refined, increasingly accurate probabilistic modeling of the input parameters is required.

A specific Case study is performed in relation to a platform and riser configuration which is proposed for production in the Northern North Sea. Results for collision between a pair of riser pipes are presented, such as stress time series, distribution of impact velocity as function of depth, probability density function of stresses caused by collision , and relative accumulated damage as a function of depth. The most important parameters influencing the collision process are in general found to be: Riser spacing, riser tension, nature of pipe surface (e.g. with or without connectors or flanges), ocean current (velocity, direction, profile) and floater motion characteristics.

COMPUTER TOOLS FOR LOAD AND RESPONSE ANALYSIS

Background

The collision analysis is performed by the integrated program system HYBER, which comprises the following modules:

- Calculation of hydrodynamic forces for the riser pipes
- Response calculation based on 3D Finite Element Models of the riser pipes
- Contact search to identify contact between the pipes and pipe deformations

In the Finite Element Module, see e.g. Amdahl et al (1988), a general 3D beam element is applied, which accounts for large rotations and non- linear material behavior. The floater motion is represented in terms of prescribed displacements (harmonic motion) of the riser top end.

Hydrodynamic load model

In the finite element representation of the riser system, each finite element is treated individually with respect to the hydrodynamic load calculations. A coarse FE mesh results in a coarse hydrodynamic representation and vice versa. The hydrodynamic module calculates drag- and lift coefficients based on the instantaneous relative position between the risers

An efficient model for calculation of forces on deep water risers exposed to ambient flow has been developed , Sagatun, Herfjord Holmås. If the risers are located close to each other, the flow pattern characteristic for a single cylinder will be "disturbed", which will influence the forces on all the relevant risers. The load model accounts for these effects in terms of pre-defined coefficient tables.

These are generated on basis of CFD calculations with extensive parametric studies for different relative positions. The mean value, amplitude and characteristic frequency of the hydrodynamic force is subsequently stored. For each analysis time step, the actual distance (dX and dY) between the risers is calculated by the Finite Element analyses, and interpolated coefficients are used.

The concept was originally developed for 2D analyses. The theory has been taken over to 3D analyses assuming piecewise constant conditions along the risers. The different 'layers' are connected by the riser model, and movement of the riser in one layer will be transferred to the neighbor layers.

Surface contact search algorithm

The contact formulation is based on a general surface-surface contact search/contact force technique. The calculations are divided into the following main steps: (i) Coarse contact search (beam/beam search) (ii) Re-meshing of beams to surface elements (if beams are close), see Figure 1 (iii) Detailed 3D surface– surface contact search (iv) Establish appropriate stiffness of the pipe surface (v) Calculate interface force (if contact) on pipe surface and re-track to beam system for further modification of the system load vector (vi) Record impulse, impact velocity, and angle between risers (see figures below) (vii) Compute stresses in the pipes.

GENERATION OF ENVIRONMENTAL AND VESSEL MOTION DATA

Background

The present paper is concerned with modeling of input parameters for current magnitude and surface floater motions within the context of riser collision analysis. The current is here modeled in terms of a given (planar) velocity profile scaled by the surface magnitude. Combination of current magnitude and surface Spar motion amplitude is identified as a highly relevant modeling issue. The interaction between forces due to current and prescribed top end motions is in general of a highly nonlinear character.

The characteristic time scale for the current (i.e. for which the current magnitude is kept constant) is 12 hours. However, the characteristic time scale for the platform motion will generally correspond to the duration of a stationary sea state. This is typically taken to be in the range of 3-4 hours. Given these different reference periods, various options for how they should be combined are available.

Statistical modeling of current velocity and floater motion

The current velocity is here represented in terms of a long-term distribution of the Weibull type. The same applies to the floater surge motion. The shape of the current profile is for simplicity taken to be the same for all cases, but with the surface velocity acting as a scaling factor. The same factor is applied for all levels of the profile. More complex representations of both the current and the floater motion can easily be envisaged. However, in order to illustrate the basic steps of the procedure, this modeling is sufficiently general. Furthermore, it is assumed that the floater motion and the current velocity refer to the same basic duration, which here is taken as 12 hours. For the floater motion, the long term distribution is assumed to represent the amplitudes for the combined low- and wave frequency response.

Each of the long-term distributions can now be subdivided into a number of intervals. For each of the intervals, the corresponding probability content can be computed. A particularly convenient scheme is to apply intervals with equal probability contents. This implies that the length of each interval (both for the current and for the floater motion) will vary.

The joint probability of each interval for the current velocity and each interval for the floater motion is now equal to the product of each of the separate probabilities (by assuming independence between the floater motion and the current velocity). For each combination of intervals, a response analysis should now be performed. Response time series are post-processed to yield probability distributions of stresses and accumulated fatigue damage. The long-term distributions of the same response quantities may in principle be obtained by a proper weighting and summation of all the corresponding distributions. This is illustrated in Figure 1 below.

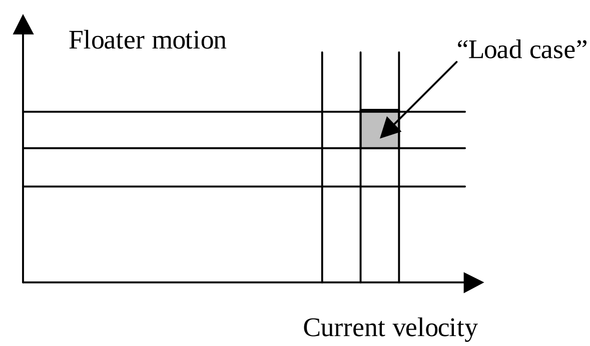


Figure 1. "Load cases" corresponding to combination of current velocity and floater motion

However, in order to obtain a sufficiently accurate long term distribution, the total number of response analyses can easily become very large. Accordingly, we consider here an alternative strategy which is based on an iterative approach. The combination of current velocity and floater motion which is responsible for the most significant contribution (in a probabilistic sense) to the long-term stress and the fatigue damage is identified. During the same process, the stress corresponding to a given return period is estimated as well as the fatigue damage for a specified service lifetime.

Procedure for iterative response analysis

It is highly relevant to perform an independent assessment of which "load cases" that represent the dominating contributions to the design stress level with a given return period. The same applies to the fatigue damage. Such an independent check will provide information in relation to the required level of subdivision for different parts of the load parameter variation range. Furthermore, such an independent assessment should give an estimate of the response level corresponding to the given return period.

In order to achieve these objectives by means of a limited number of analyses, the following stepwise procedure is applied:

A. Perform initial response analysis and statistical estimation:

- Specify two current velocities for which response analyses are to be performed. Specify a base case floater motion to be applied for both analyses.
- Perform the response analyses and identify the critical cross-sections with respect to contact stress and accumulated fatigue damage. If no collision occurs for the lowest current velocity, select a higher velocity until collision takes place.
- Estimate the probability distribution for the contact stresses which correspond to both current conditions. Fit a linear relationship between the parameters of this distribution and the current velocity. Fit a relationship of the same type for the fatigue damage due to riser collision.
- Specify one additional floater amplitude for which response analysis is to be performed. This amplitude is to be applied in combination with the highest current velocity.
- Estimate the corresponding probability distribution of the contact stress obtained from the time domain simulation. Fit a linear relationship between the parameters of this distribution and the floater motion amplitude
- Estimate the fatigue damage for the critical cross-section based on the response analysis for the additional floater amplitude 4. Fit a linear relationship between the fatigue damage and the motion amplitude.

In relation to the linear relations between response and "load parameters", cut-off levels should be applied below which no response occurs. This is accounted for indirectly by checking that the dominant "load cases" obtained in step B below are located above the cut-off levels.

B. Perform reliability analysis to identify main contributing load cases:

- Based on the fitted linear relations, a reliability analysis is performed. The stress response level is treated as a parameter that can be varied. The relationship between this response level and the probability of exceedance is then obtained.
- From this relationship, estimate the response level with a given return period. Identify the load cases which gives the highest contributions to this response level based on the fitted linear relations.
- For the fatigue damage, the main contributing load cases are identified based on importance factors corresponding to the dominating product of expected damage and frequency.

C. Update response analysis and refine estimation of main load cases:

- Perform new response analyses for the load cases which give the highest contribution to the contact stress and the fatigue damage.
- Update the relationships between response level (also including fatigue damage) and the load case parameters by including the additional response analyses
- Perform a new reliability analysis bases on the updated relationships, and identify the new load case parameters that are responsible for the dominating contributions.

If the estimated load case parameters from the different steps change "too much", intermediate conditions also need to be analysed. If it is found during the various steps of the analysis that the the most critical cross-section changes along the riser, several candidates may have to be considered.

The different steps are illustrated in relation to the Case study below.

CASE STUDY: RISERS SUSPENDED FROM SPAR BUOY

General

The case study platform is a Spar buoy with a trusswork at the lower part. The diameter of the upper cylindrical part of the platform is 40m. An overview of the layout is shown in Figure 2. The spacing between the risers is 15 diameters at the platform (within the moonpool), and 40 diameters at the seabed. This implies that the risers are almost vertical for the present water depth of 900m.

It is found that a top tension of 2.2 times the submerged weight (i.e. Top Tension Ratio (TTR) equal to 2.2) will imply negligible collision frequencies. However, in the present analysis, a reduced TTR of 1.8 is applied as a base case value in order to provoke collisions.

For the case study, two production risers with identical diameter were selected. The current is acting in-plane, which corresponds to 0° in the FE-model.

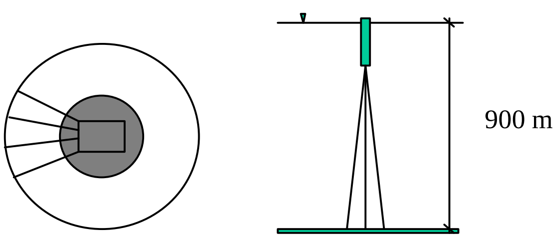


Figure 2 Case study riser configuration.

FE – model

The finite element model consists of beam elements representing the two production risers. The risers are assumed to be located in the same plane. The structural system is relatively slender with a length/diameter ratio of approximately 3500.

The risers are modeled from the Spar buoy to the seabed, giving a total length slightly above 1000m. As mentioned above, a TTR of 1.8 is applied in the present analysis. This is done in order to obtain more collisions for the case study purpose. A parametric study on the effect of TTR is also performed below.

The time increment in the analysis is 5 ms, and the analysis time is 1200 seconds (8 floater periods), Time consumption: Approx. 10 times the real time (3.3 hours *cpu* for 1200s on a PC).

The floater motion represents a substantial fraction of the total speed which is experienced by the riser. This motion is accordingly applied in order to correct the constant ocean current (with a reduced correction for the lower parts of the risers). The floater motion is modeled as a prescribed time-harmonic displacements for the uppermost node with a period of 150s. The resulting "effective current" along the riser is hence composed of a constant part + a harmonic varying part with the same period of 150s.

ITERATIVE RESPONSE ANALYSIS : RESULTS

Step A

Response analyses are first performed for two different current velocities with a fixed floater amplitude equal to 10m. These current velocities are respectively equal to 1.3 m/s and 1.7 m/s. The base case TTR is set to 1.8

The current velocities obtained from the long term distribution which corresponds to return periods of 1 year and 100 years are given as 1.25 m/s and 1.7 m/s, respectively. However, for the present analysis the lowest current velocity applied is taken as 1.3 m/s. The highest velocity applied corresponds to the 100 year value of 1.7 m/s. For the Spar surge motion (at keel level), a harmonic motion with amplitudes of both 5 and 10 m are applied in order to investigate the effect of varying platform motion. A period of 150 seconds is employed.

Results for current velocity equal to 1.3 m/s

The velocity at the top of the riser which is induced by a vessel motion amplitude of 10m and a period of 150 seconds is 0.42 m/s. The "total current" accordingly varies between 1.3 - 0.42 m/s = 0. 88 m/s and 1.3 + 0.42 = 1.72 m/s.

The impacts occur in a zone with length of 400 m at the upper parts of the risers, (between 100 and 500 m). The maximum impact speed is roughly 0.9 m/s which occurs at a depth of about 350m.

The contact stress probability density is shown in Figure 2 (corresponding to all the collisions along the riser). It is observed that around 80% of the contact stresses are less than or equal to 30 MPa. The peak of the density function is found between 10 and 20 MPa. A probability density function of the Weibull type is fitted to the histograms.

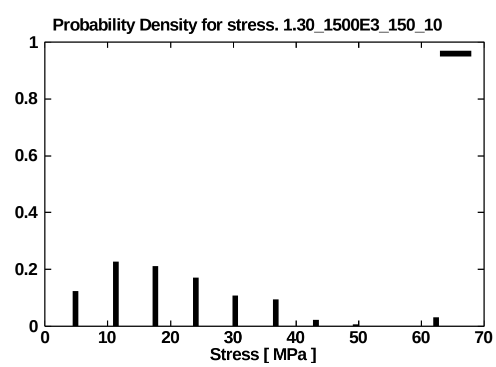


Figure 2 Probability density of impact stress.
Current velocity is 1.3m/s

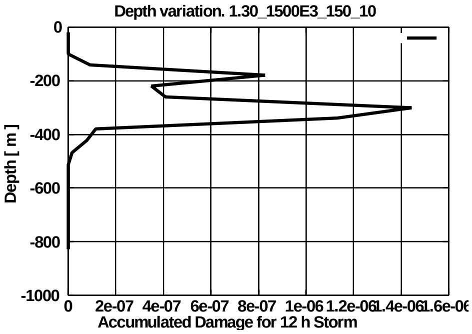


Figure3 Accumulated damage along riser.
Current velocity is 1.3 m/s.

Based on the stresses occurring within a given riser segment, the accumulated damage which corresponds to a given duration can be computed. The damage along the riser, which is computed for a duration of 12 hours, is shown in Figure 3. This quantity accounts for the product of stress level and the number of impacts at that particular level. The highest value occurs for a depth range from 150 to 350 m. Two distinct peaks occur at roughly the same locations as for the maximum impact speed.

Results for current velocity equal to 1.7 m/s
For the 100 year current ((1.7 m/s), the total current velocity varies between 1.7 - 0.42 = 1.28 m/s and 1.7 + 0.42 = 2.12 m/s by including the floater motion. As seen from Figure 4, the peak stress is about 120 MPa, which is of the order of 25 % of the yield stress for the riser pipe.

The impact zone has roughly the same extent as for the previous case. As seen from Figure 4, about 80 % of the stresses are less than 40 MPa. A Weibull model is fitted to the histograms also for the present case.

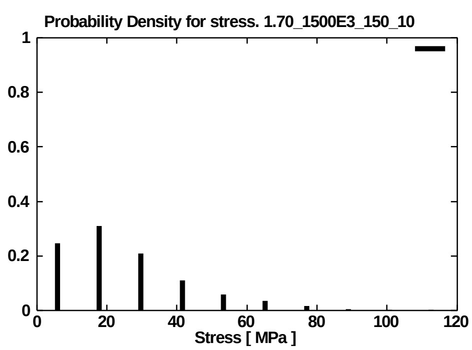


Figure 4 Probability density of stress.
Current velocity is 1.7 m/s

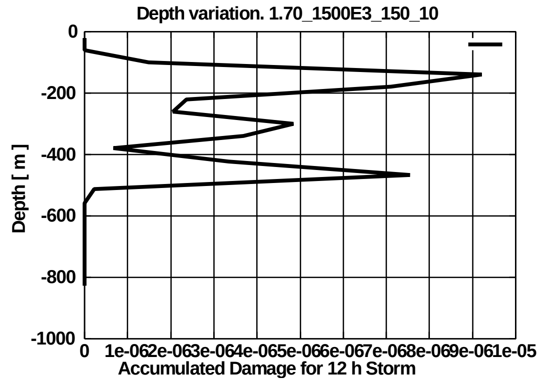


Figure 5 Accumulated damage versus depth
Current velocity is 1.7 m/s.

For the accumulated damage shown in Figure 5, the locations of the maximum values are shifted upwards to about 150m. The maximum value is also increased as compared to the two previous cases as expected. We consider a cross-section which is located at a depth of around 150m and apply the damage values which correspond to the uppermost peaks of the diagrams.

Effect of reducing floater motion amplitude
The amplitude of the floater motion is subsequently reduced from 10 to 5m. The TTR is equal to the base case value of 1.8, and the current velocity is 1.7 m/s. The peak stress which occurs during the simulation is now approximately 130 MPa.

The impacts still occur within the same zone as before, with the maximum velocity now being roughly 1 m/s. This is somewhat smaller than for the 10m motion amplitude.

The probability density in Figure 6 shows that 80% of the stresses are less than 40 MPa. However, for this case the peak probability density occurs for a much smaller value (less than 10 MPa) than for the 10m amplitude (for which the peak occurs close to 20 MPa). An exponential distribution is fitted to the histograms for this case. This may also be regarded as a special case of the Weibull model.

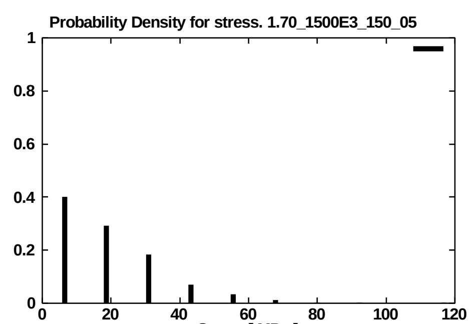


Figure 6 Probability density of maximum stress.
Motion amplitude is 5m

The maximum damage occurs according to Figure7 at the same depth of 150 m as for the 10m amplitude. However, the peak damage is surprisingly increased by a factor of 2 compared to that case, even if the other peaks are somewhat reduced.

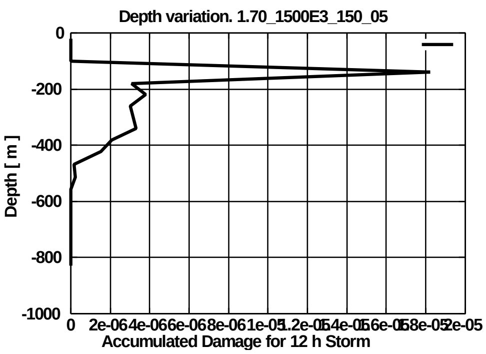


Figure 7 Accumulated damage along the riser. Motion amplitude is 5m.

Step B: Reliability analysis

Based on the fitted probability distributions for the three cases which are analysed, the scale (σ) and shape (η) parameters of the Weibull distribution are estimated. These are subsequently expressed as linear functions of the current velocity and the floater motion. This can be expressed on the form

$$\sigma(U_C, A) = c_1 + c_2 \cdot u_c + c_3 \cdot a$$

and

$$\eta(U_C, A) = c_4 + c_5 \cdot u_c + c_6 \cdot a$$

where c_1, c_2, c_3, c_4, c_5 and c_6 are constants, U_C is the current velocity and A is the floater motion.

Introducing the local stress maxima as a random variable, the probability that an arbitrary maximum will exceed a given threshold value can be established. This is achieved by introducing a limit state function of the following form:

$$g(C,x) = C - x$$

where C is a selected threshold value for the local maxima, and x represents the local maxima considered as a random variable.

We now apply a standard normal variable, U_1, to represent the statistical variation of the local maxima, and hence introduce the following transformation:

$$F_X(x) = 1 - \exp\{-(x/\,\sigma(U_C, A))^{\eta(U_C, A)}\} = \Phi(u_1)$$

where u_1 is the standard normal variable, and $\Phi(\cdot)$ is the standard cumulative normal distribution function. This equation can now be solved with respect to the variable x, which subsequently is inserted into the failure function. The resulting expression becomes:

$$g(C,U_C, A,U_1) =$$

$$C - \exp\{(1/\eta(U_C, A)[\ln(-\ln(1-\Phi(u_1)))] + \ln(\sigma(U_C, A))\}$$

The sought probability (i.e. the probability that the variable x exceeds the selected threshold C) now accordingly corresponds to the probability that the present limit state function becomes negative.

This limit state function can also be expressed solely in terms of normalized variables by utilizing the Rosenblatt transformation. This implies that the following relations between the initial variables and the two additional normalized variables U_2 and U_3 are applied:

$$F_{Uc}(u_c) = 1 - \exp\{-(u_c/\sigma_c)^{\eta_c}\} = -\Phi(u_2)$$

and

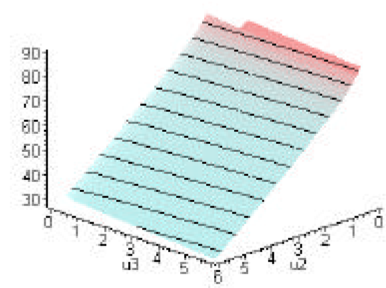
$$F_A(a) \quad = 1 - \exp\{-(a/\sigma_a)^{\eta_a}\} \; = -\Phi(u3)$$

where the Weibull distributions for both the current velocity and the amplitude have been introduced.

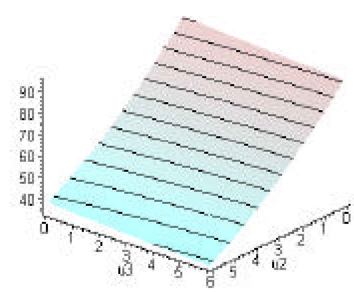
By inserting the proper values of the parameters that apply for the different distribution functions and the constants of the "response surface" relations, the following version of the limit state function as expressed in terms of the three normalized variables is obtained.

In order to identify the probability of failure (or equivalently the reliability index), the minimum distance from the origin in the normalized space to the failure function is now required. This solution cannot be found analytically based on the present highly nonlinear function. Accordingly, we expand this expression in a second order Taylor series in each of the three variables (around the point (u_1=2,u_2=2,u_3=2)).

A comparison between the original and the approximate expression is shown in Figure 8 for the case that the variable u_1 is set equal to 2, and the value of the threshold C is set equal to 60.



(a) Original failure function



(b) Approximate failure function

Figure 8 Comparison between (a) original and (b) approximate failure surface.

We are now in a position to compute the "design point" with coordinates (u_1^*, u_2^*, u_3^*) as a function of the threshold value C. This is the point on the failure surface for which the distance to the origin has its minimum value. Furthermore, the reliability index and the corresponding probability can be expressed as:

$$b = \sqrt{(u_1^*)^2 + (u_2^*)^2 + (u_3^*)^2} \quad \textit{and} \quad p_f = \Phi(-b)$$

As an example, we illustrate how the 100-year stress level can be estimated from the present expressions: The expected number of local stress maxima per time unit is first required. This is estimated by counting the number of collisions for each of the load cases which are analysed. Furthermore, an estimate of the limits for the current velocity and the floater motion below which no collision occurs is required. For the present case, this leads to a rough estimate of 560 stress maxima (i.e. collisions) per year. The total expected number of stress maxima which occur during 100 years then become equal to 56000. Inverting this number leads to a probability equal to 1.8 10^{-5}.

From the expressions above, it is found that this probability corresponds to a reliability index equal to 4.14. This corresponds to a stress level C which is equal to 46 MPa. Furthermore, the design point for this case is given by the following coordinates:

$U_1 = 1.7$ $U_2 = 3.7$ and $U_3 = 0.8$

The corresponding coordinates in the "basic space" are given by

X = 46 MPa U_C = 1.5 m/s A = 3.6m

This implies that a further response analysis should be performed for a load case with current velocity and floater amplitude corresponding to these values. This is illustrated in the next step below for the current velocity. For the floater amplitude, it is assumed that the response surface already obtained is sufficiently accurate.

Strictly, a weighting of the different load cases according to the number of collisions which occur for each case should be performed. This implies that the "highest load cases" would get increasingly higher weight. It was found that the effect of applying such a weighting was negligible with respect to the location of the design point. However, the shape of the failure surface itself was modified somewhat with a "stretching" towards higher load cases.

For the fatigue damage, the main contributing load cases are identified based on importance factors corresponding to the dominating product of expected damage and frequency. It is found that the main contributions are due to load cases with a current velocity around 1.3 m/s and a floater amplitude of 2m. The total damage is estimated as 5.6 10^{-5} referred to a duration of 20 years. This is well within the acceptance criteria, also including relevant safety factors.

Step C: Updated response and reliability analysis

Based on the identified load case region giving high contributions to the exceedance probability, we accordingly perform a new response analysis for a current velocity equal to 1.5 m/s.

Results for current velocity equal to 1.5 m/s

The "total current" now varies between 1.5 - 0.42 m/s = 1.08 m/s and 1.5 + 0.42 = 1.92 m/s. The peak stress (assuming a homogeneous pipe) is approximately 105 MPa. The extension and location of the impact zone is roughly the same as for the 1.3 m/s case.

The stress probability density is shown in Figure 9. Also for this case, around 80% of the contact stresses are less than 30 MPa. However, the peak between 10 and 20 Mpa is now much higher than for the current velocity of 1.3 m/s.

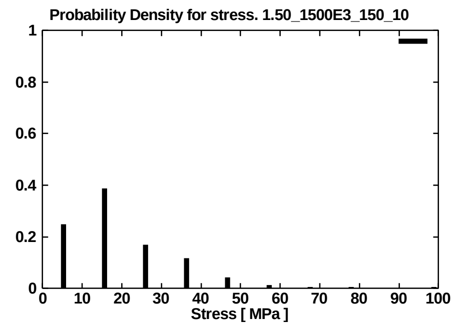


Figure 9 Probability density of impact stress
Current velocity is 1.5m/s

The damage along the riser is shown in Figure 10. The highest values occur at depths of about 200 and 300m. However, we simplified assume this maximum value to occur at the same cross-section as before.

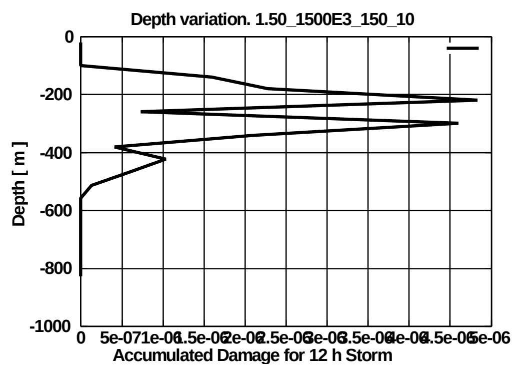


Figure 10 Accumulated damage along riser.
Current velocity is 1.5 m/s.

Similar to before, we express this in terms of normalized variables. Subsequently we approximate the failure functions by means of a second order Taylor series expansion. The new design point can then be obtained, as well as the updated relations between stress threshold and probability of failure. It was found that the response relations changed somewhat, but the design point coordinates shifted only slightly. The new design point for the current corresponds to a velocity of 1.45 m/s, and the new stress levels was found to be 48 MPa. This gives reasons to stop the iteration due to the close agreement with the previous results.

For the fatigue damage, the main contribution is still found to be due to the same combination of current velocity and floater amplitude as before. However, the estimated value of the fatigue damage was increased somewhat by including the new "load case". This is due to a nonlinear relation for the new response surface. This indicates that additional load cases with current velocities in the interval between 1.3

and 1.5 m/s is required in order to obtain a sufficiently accurate estimate.

SUMMARY AND CONCLUSIONS

A procedure for assessing the severity of collision problems for deep-water riser arrays is described A specific Case study is performed in order to illustrate the methodology. The surface current velocities are in the range between the 1-year and 100-year extreme values. The following observations of key response quantities are made:

- Peak stresses of the order of 130 MPa are observed. These stress levels are relevant for uniform pipes and will be much increased for cases with a connector on one the risers.
- The extension and location of the zone where impacts occur seem to be quite stable.
- Increasing vessel motion amplitudes seem to increase the average stress level, but the tendency is not so clear.
- The "load cases" which provide the main contributions to the 100-year stress level are as anticipated different from those which give main contributions to the fatigue damage

The present iterative approach should hopefully prove to be useful in order perform a preliminary assessment of the main contributing load cases. It should also be of value in order to obtain an independent check on results obtained by a direct subdivision of the whole "load case" intervals.

Further studies on the simulation lengths required to obtain stable response statistics should obviously be performed. Similarly, convergence studies on the number of load cases to be analysed in order to obtain stable estimates of the design values need to be performed.

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