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DEEPWATER RISER INTERACTION. COMPUTATIONAL METHOD AND VALIDATION

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ABSTRACT

A method for predicting interaction between risers is presented. The method is efficient and handles different riser systems exposed to complex environmental data. To achieve this, the method utilizes pre-established data for forces on risers in close proximity. Interaction effects concerning mean values as well as the dynamic forces at vortex shedding frequencies are stored.

The interaction effects cause large wake induced oscillations (WIO), and the vortex induced vibrations (VIV) are influenced as well. The method uses the database of forces in a strip theory manner to obtain excitation forces on risers and other slender bodies exposed to current.

The method is implemented in a non-linear dynamic finite element tool, HYBER. During the simulation, the clearance between the risers is followed up. If collisions occur, relevant data are recorded, and the simulation continues. Fatigue and possible single event damage are assessed. In the present paper, results from the method are compared with comprehensive measurements in model scale, and the computed results show good agreement with the measurements.

Databases exist for bare cylinders with equal and unequal diameters as well as for two geometries of strakes.

KEYWORDS: Riser interaction, Collision assessment, Computational method, Validation vs. measurements

INTRODUCTION

The possibility for interaction between risers increase for increasing water depths. This is the case for top tension risers (TTRs) as well as for flexible risers and umbilicals. The interaction and clashing between long risers represents a highly non-linear problem which is hard to predict. The interaction problem is also an issue for overhead power transmission lines, and there are methods developed for that case, see e.g. Diana et al. (1999). The interaction between cylinders in water is treated experimentally by Zdravkovich in a number of papers, see e.g. Zdravkovich (1987). Similar measurements have also been performed by Price and Paidoussis (1984). The data that are given from the referred literature are mean values of drag (in-line force) and lift (cross-flow force) depending on relative position between the cylinders. In a simulation program for riser dynamics in proximity to other risers, the dynamic part is also needed in order to be complete. Many investigations also exist where instability and onset of dynamics are treated. Paidoussis and Price (1988) consider the instability of cylinders in an array. Wu et al. (2001) have also considered onset criteria for instabilities for a cylinder in the wake of another.

Likewise, measurements of pairs of interfering cylinders that are oscillating individually are published., see e.g. Zdravkovich (1985). These publications are very important for observing how the interaction phenomena affect the motions of cylinders in close proximity. However, they can not be used directly to compute the response of long risers. The referred tests are done for cylinder sections that on average have a constant distance to each other. Long risers will have large oscillations in a different time scale than VIV. The low frequency wandering is called wake induced oscillations (WIO). These oscillations are excited by the continuously changing mean forces as the risers change the average position relative to each other. The use of information on local VIV from tests on short sections will be difficult. The mass ratio, natural frequency, preferred oscillating mode, etc. will have to be in correct relation to the tests with short sections. If the direct use of information on oscillation response had been possible to use on long risers, it would have been a so-called response based model.

An alternative option is to apply a so-called force based model. This kind of model is using forces that are established for cylinder sections that are in proximity. The forces can be used on risers that are modeled numerically (e.g. by FEM), and the risers are free to respond according to the structural properties prevailing, due to stiffness, tension, initial shape, etc. The forces may be established by computations with CFD program or by lab measurements. In Sagatun et al. (2001) dynamic simulation in 2D is reported with the use of forces from CFD computations. The basis of forces contained mean forces as well as dynamic forces at the vortex shedding frequency.

The present paper is reporting how to use such a data base of forces on long risers by the use of strip theory. Methodologies based on computation of mean forces are described by e.g. Huse (1993) and Wu et al. (2002). Huse uses wake theory according to Schlichting to compute the reduced drag for the shielded risers in an array. This type of program is able to obtain the new equilibrium position due to interaction, and is thus able to indicate if contact may be experienced. Wu et al. (2002) are using a free streamline model to obtain the inflow on the cylinder in the wake. Still the model is based on representation of mean forces.

In the present paper, a methodology to simulate the dynamics of the risers in all timescales is described. The simulations are done in time domain, and the process is followed also after hits occur. Results from using the method are compared with results from measurements.

NOMENCLATURE

A_{0_L} - Limiting amplitude used in damping formulation. Subscript L for cross-flow (lift) direction.

$C_{L\_mean}^{(2)}$ - Non-dimensional force coefficient. Subscript L for cross-flow (lift) direction. Subscript $mean$ for mean value part. Superscript (2) for cylinder 2, downstream.

$C_{L\_osc}^{(2)}$ - Non-dimensional force coefficient. Subscript part osc for oscillating part of force.

D - Diameter

$F_L^{(2)}$ - Force. Subscript L for lift, Superscript (2) for cylinder 2, downstream.

$F_{L\_damp}^{(2)}$ - Damping force. Subscript L for cross-flow (lift) direction. Superscript (2) for cylinder 2, downstream.

$f_{C_L}^{(2)}$ - Frequency of oscillating part of force. Subscript C_L for cross-flow (lift) part of force. Superscript (2) for cylinder 2, downstream.

t - time

U - Instantaneous ambient flow velocity

x - Distance between the two cylinders in local x-direction. Local x-axis is in the flow direction at actual section (element).

y - Distance between the two cylinders in local y-direction

$\dot{y}^{(2)}$ - Velocity of structure in local cross-flow direction. Superscript (2) for cylinder 2, downstream.

$\sigma_{C_L}^{(2)}$ - Standard deviation of the oscillating part of force coefficient. Subscript C_L for cross-flow (lift) part of force. Superscript (2) for cylinder 2, downstream.

θ - Argument in sine function.

ω - Angular frequency of oscillation, varying with time.

THEORY

The method is based on pre-established coefficients for the parameters included in the model. The method has some similarities to the Morison type of loading. However, Morison's equation is first of all developed to compute the response in a flow that is oscillating, as for a structure in waves. While Morison's equation is made to compute the response in oscillating flow, the present model handles arbitrary slowly varying current. The WIO is excited by the varying mean force, depending on relative position. The force at vortex shedding frequency is also important to represent. In the case of two cylinders in close vicinity of each other, the vortex shedding will be influenced. This statement is first of all valid for the cylinder in the wake. However, also the shedding from the up-stream cylinder is influenced. This is realized both on the frequency as well as on the amplitude of dynamic force. In order to be able to represent the relevant dynamics, it is needed to have records of force data in both directions, in-line and cross-flow, for both the cylinders. For one particular degree of freedom, the force is represented by three numbers, i.e. the mean value, the standard deviation of the varying part and the frequency of the varying part. Which means that for each of the two cylinders, 6 numbers are given for each relative position.

The method is based on a quasi-static assumption, which means that data are recorded when the cylinders are kept fixed. In a dynamic simulation, the excitation at a given time step is taken as the forces recorded at the instantaneous relative position. The necessary data are taken from the database for the actual relative position. Interpolations are done between positions where recording exist. Where there are large variations, the recordings should of course be done in a dense grid. The force model is given by the following equation, the cross-flow direction for the cylinder in the wake is given as example:

$$F_L^{(2)} = \frac{1}{2}\rho D U^2 (C_{L\_mean}^{(2)} + C_{L\_osc}^{(2)}) + F_{L\_damp}^{(2)}$$

$$C_{L\_mean}^{(2)} = C_{L\_mean}^{(2)}(x,y)$$

$$C_{L\_osc}^{(2)} = \sqrt{2}\sigma_{C_L}^{(2)}(x,y)\sin\left(2\pi \frac{f_{C_L}^{(2)}(x,y)U}{D} t\right)$$

The sine function is in the above equation given in a symbolic form. For a constant frequency, the way of writing the argument is functioning well. However, when the frequency change due to the interaction effects, the sine function will jump, even for a small change in frequency. It is important that argument is a continuous function. The treatment of the argument is as follows:

$$\sin\theta$$

where

$$\theta = \int_0^t \omega(t')dt'$$

The practical implementation is as follows:

$$\theta_{(n+1)} = \theta_n + 2\pi \frac{f_{C_L}^{(2)}(x,y)_n U}{D} dt$$

Concerning the hydrodynamic damping, there are many formulations. There are force models where the damping is treated through a relative velocity formulation. Our force model is based on the ambient flow, and the damping is treated explicitly. The following damping model is implemented:

$$F_{L\_damp}^{(2)} = \frac{1}{2}\rho D C_{L\_osc}^{(2)} U^2 \frac{1}{A_{0\_L} 2\pi f_{C_L}^2(x,y)} \dot{y}^{(2)}$$

$C_{L\_osc}^{(2)}$ is the amplitude of the force in the actual degree of freedom, in this case the lift force on cylinder 2. A_{0_L} is a limiting amplitude where the excitation should be reduced to zero according to the self-limiting tendency in lock-in VIV. In the in-line direction, the limiting amplitude is set to 0.35 D, and in cross-flow it is set to 1.1D. The added mass is another important parameter, which has to be modeled. In our implementation it is simply set equal to 1.0.

A drag amplification due to VIV is implemented according to Sarpkaya (1978):

$$C_{D\_mod}^{(2)} = C_{D\_mean}^{(2)}(x,y)\left(1 + 2\frac{A_L^{(2)}}{D}\right)$$

$A_L^{(2)}$ is computed based on the actual cross-flow response. The cross-flow velocity history is continuously filtered and the actual VIV frequency is used to estimate the oscillating displacement amplitude. The theory and implementation is more thoroughly described in Holmås et al. (2002).

There are assembled data for a number of different configurations. Data exist from computations as well as from measurements, for smooth cylinders with equal as well as unequal diameters. In addition, there are measured data for two different strake geometries. All data are assembled in databases to be used by the simulation program. An example from one database is given in Fig. 1. A validation of the database is found in Herfjord et al. (2002). The definition of the local coordinate system is given in Fig. 2.

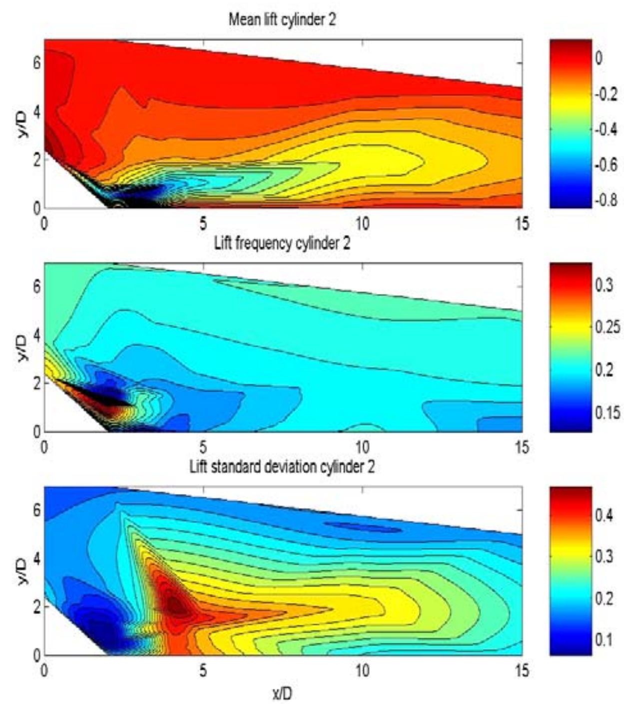

Figure 1. Data for lift force on cylinder 2, i.e. in the wake of an up-stream cylinder. The data are from the case with two smooth cylinders of equal diameter, as measured at DHI (Bryndum and Andersen, 1999).

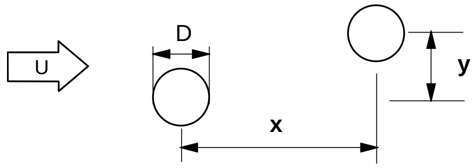

Figure 2. Definition of local coordinate system.

RESULTS. COMPARISON BETWEEN COMPUTATIONS AND MEASUREMENTS

Test set-up, model and instrumentation

The measurements were done at Marintek (Baarholm (2004), Baarholm and Kristiansen (2004)). Two model risers were instrumented quite thoroughly to be able to record or deduce the following quantities:

- Number of hits
- Relative velocity at hit
- Distribution of hits along risers
- Vortex induced motions (VIV)
- Wake induced oscillations (WIO)
- Global forces at ends
- Top tension

VIV were deduced from recordings by accelerometers, 31 for recording of in-line motions and 19 for cross-flow motions. The relative velocities at hits were found by integration of accelerations. The position of each hit was recorded by measuring of conductance between conductive tape wrapped around the risers. The wrapping was divided into sections, so that the position could be decided, 10 sections were used. For bare riser, the sections were distributed one meter on either side of the mid depth, and for straked riser 2.5 meter on either side. To be precise, each section were 0.2 m long for bare riser and 0.5 m for straked riser, see also Fig. 3. The WIO are deduced from the global end forces and the set-down at the top.

The risers were made of reinforced fibreglass. This material has a modulus of elasticity about one tenth of steel. By this it was easier to obtain dynamics of the risers that could contain high modes. Within the velocity range used in the tests, bending modes in cross-flow direction up to mode 6 could be obtained. The diameter of each riser was 20 mm. The mass ratio $m^* = m/(\pi/4)D^2 = 1.94$. The scaling of the quantities is done according to the so-called equal velocity scaling, which means that velocity in the model tests is equal to the prototype velocity, Huse (1998). The velocity scaling makes it possible to do the tests in model scale dimensions, yet with prototype scale materials. It is also the case that the Reynolds number is higher with equal velocity scaling. However, the scaling method makes it impossible to scale the results directly to prototype scale. This is not considered a weakness, since the main porpose with the tests were to use the results as basis for validation of computer program for interference and clashing. An overview of the set-up is given in Fig. 3. Details on set-up and instrumentation are found in Baarholm et al. (2005). The conditions are varied by parameters given as follows:

- Current (towing) velocity
- Center-to-center distance
- Inflow angle
- Top tension
- With and without strakes
- With and without bumpers

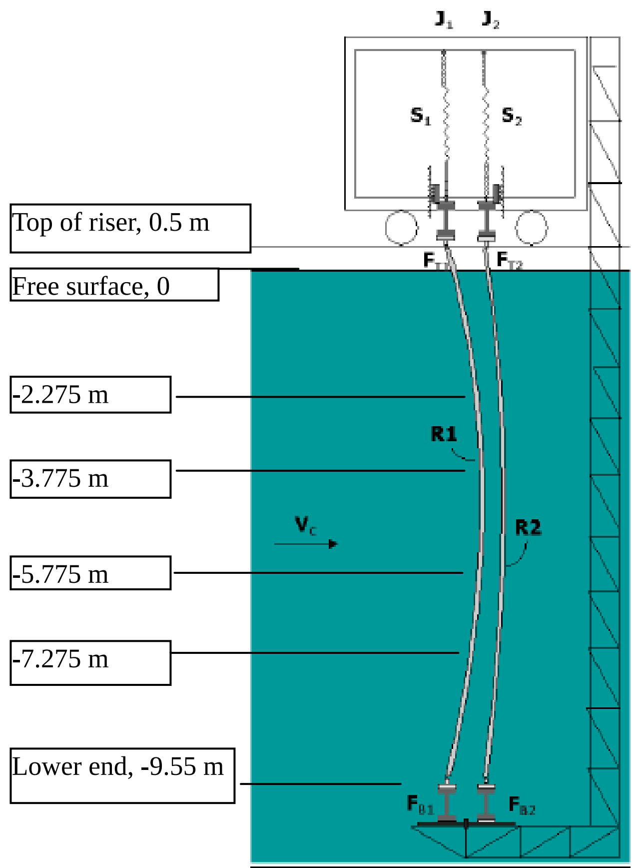

Fig.3. An overview of the set-up for the dual riser clashing tests. The current is made by towing the system in calm water, making a uniform ambient flow against the risers. The clashing sensors are placed between –5.775 m and –3.775 m in the case of bare

risers, and between –7.275 m and –2.275 m in the case of straked riser.

The strakes were triple start with height h/D=0.15 and pitch P/D=10. The bumpers were included to investigate the possibility to "direct" the hits to positions that are prepared to take hits without damaging the riser itself. There were placed two bumpers at each riser. The bumpers were positioned equal to 10 % of the total length of the riser from the mid depth. There were bumpers at both risers at equal depths for each riser. The inflow angle ϕ can be defined by referring to Fig. 2:

$$\phi = \arctan\left(\frac{y}{x}\right)$$

Measured vs. computed results

The computer program is set up for recording and reporting data related to hits between the risers. For each simulation, the number of hits and the distribution of them along the riser is recorded. The relative velocity between the risers at each hit is also recorded, as center to center velocity, in the model tests named as IL velocity. In the case of steel risers, the resulting deformation can be transformed to stresses, and the fatigue can be computed. The program can be set up to a large number of velocity profiles and current directions, in addition to a superimposed low frequency motion of the floater the risers are attached to. The set-up can be done according to a scatter diagram, and fatigue due to clashing can be computed in a stringent manner. For a plastic material, there is a different relation between the hit velocity and damage, so fatigue will not be an issue for this investigation.

The results can be presented as time plots, distributions along the length of the riser as well as probability distributions. In this case, the distribution of hits along the riser and the probability distribution of relative velocity at hits will be compared.

The first comparison is for a case where the two risers were placed in tandem. The center to center distance was 10 diameters, and the velocity was 0.7 m/s. The top tension was 300 N for both risers, and the top spring stiffness was 1065 N/m, as for most of the tests. Some tests were done with lower top tension, and some with unequal top tensions, the upstream riser had higher tension in that tests to check if that was favourable. The measured and computed results for the distribution of hits along the riser is compared in Fig. 4. The time duration of the test and the simulation was about equal. The measured number of hits was 116, while 558 hits was recorded in the simulation. This is an overestimation, however it is emphasized that it is a conservative estimation. It is also seen that the computation predicts contact over a longer part of the riser than actually measured. For larger velocities, it seems clear that hits would occur over larger length than there were

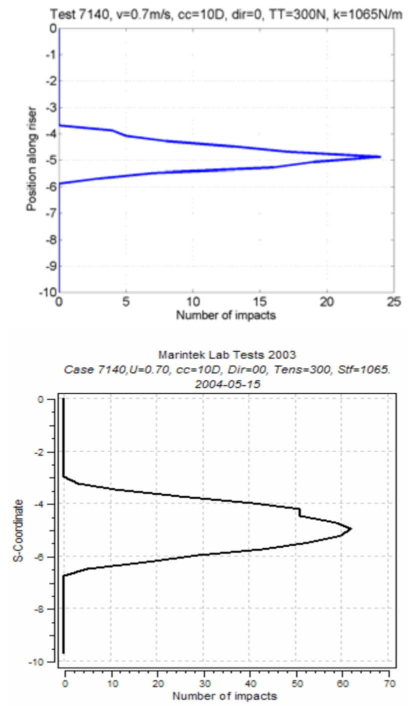

Fig. 4. Distribution of hits along the riser length. Upper figure is from measurements, lower figure is from computations.

sensors. There were hits on every sensor in the referred test, however we do not think there were hits outside in this case.

For this test (Test No. 7140), we have also compared the velocity at hit. This is done by presenting the probability distribution of the relative velocity at hit, see Fig. 5. The distributions are similar to each other, and the maximum velocity is slightly overestimated by the computation. One characteristic to be noticed is that there occur negative velocities from the experiments. This could be considered questionable, since the velocity component is along the axis between the two centers of the risers, IL velocity. However, there is also a velocity component perpendicular to the IL velocity, due to cross-flow VIV. This component is larger than the IL velocity, and a plausible explanation is that the two risers have been in touch while they pass each other in negative IL direction.

If we increase the velocity to 0.9 m/s, we get the picture as shown in Fig. 6. The test was repeated, and it is seen that there is a difference in the number of hits between the two tests. The number of hits are 103 and 220, respectively. The computations predict 889 hits. The simulation lasted for 46 seconds, while the

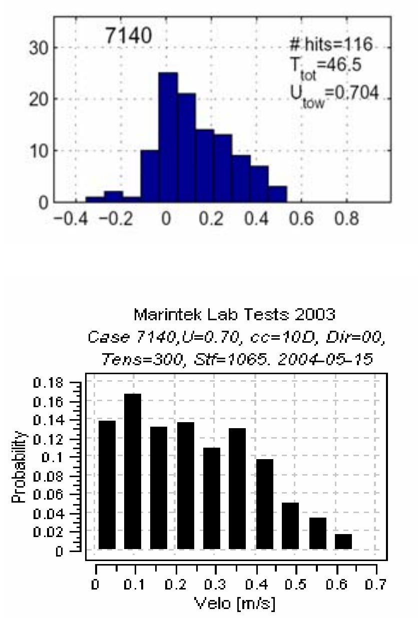

Fig. 5. Probability distribution of velocity at hit, test No. 7140. Upper figure shows results from the measurements, lower part is from computations.

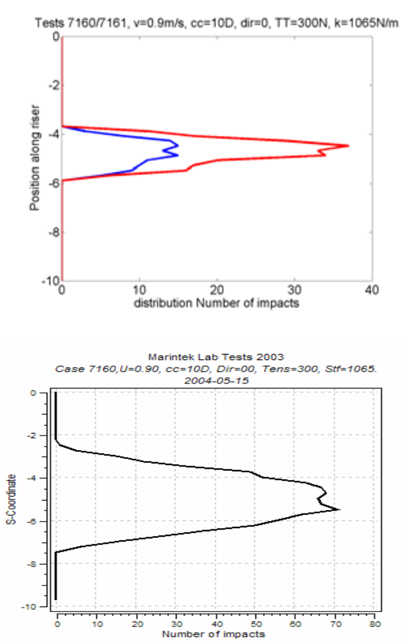

Fig. 6. Tests with current velocity 0.9 m/s. Upper part experiments. Two repeated tests.

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measurements lasted 36 seconds. In this case we suspect that there were hits outside the range of sensors. This example shows again that the program is on the conservative side. Moreover, it demonstrates the level of complexity of the process, since two tests with presumably equal conditions showed a large difference in number of hits. In order to extract data and compare results in a more concentrated manner, we have taken the maximum hit velocity at each run. The example given is for the case of risers in tandem, as for the previous cases, however with top tension 200 N. The comparison is shown in Fig. 7. It is seen that the simulations predict max hit velocities that are on the conservative side, however, not grossly over predicted.

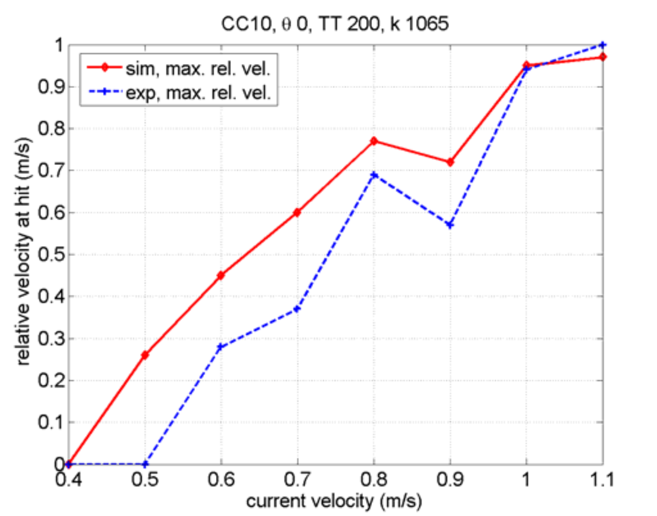

Fig. 7. Comparison of maximum hit velocity each run, measurements vs. computations.

The case with strakes is simulated in the same manner, however with database from measurements with riser sections equipped with stakes of the same geometry as used in the long riser tests, i.e. h/D=0.15, P/D=10. The database is extracted from tests at DHI Water and Environment (Bryndum and Jørgensen 2002). In the case of strakes, the sensors for hits covered 5 m around the mid depth of the risers. This was decided on basis of previous tests with long risers with strakes, Huse (1998). The tendency was that hits occurred over a longer length than for bare risers. In addition, the risers tend to cling to each other without repeated hits. This behaviour lead to the use of time period of "hugging" related to total test period as a parameter from the measurements, see Baarholm et al. (2005). The hugging tendency was also depicted in the computations. However, the example presented had more distinct hits, the "hugging ratio" was reasonably small. The test is with center distance 10D, heading angle 10 degrees, top tension 300 N and top tension stiffness 1065 N/m. The current velocity was 0.7 m/s. For higher velocities, the risers hugged to each other. For the actual test, No. 4320, the number of hits recorded in the measurements were 114, while in

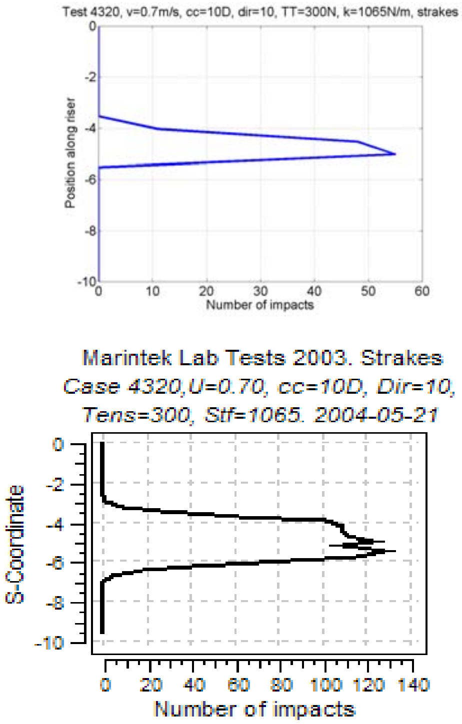

Fig. 8. Distribution of hits along the length of the risers in the case of strakes, CC=10D, current heading 10 degrees, top tension 300 N, top tension stiffness 1065 N/m. The current velocity was 0.7 m/s. Upper figure is from the measurements, lower figure from computations.

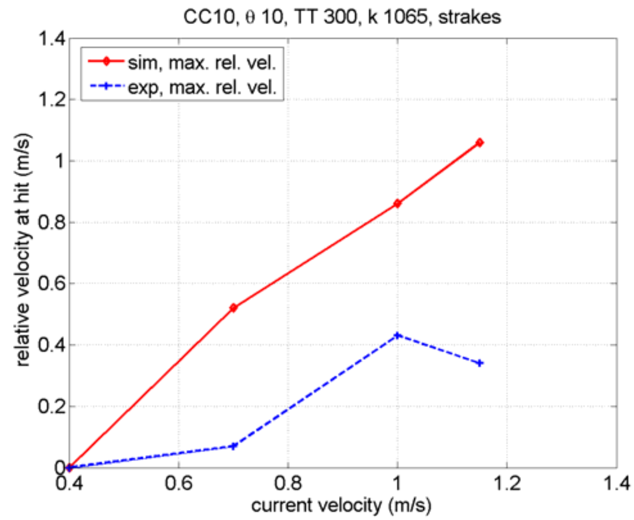

Fig. 9. Maximum hit velocity for tests with strakes, measurements vs. computations. Center distance 10D, inflow angle 10 degrees, top tension 300 N, top tension stiffness 1065 N/m.

the computations, the number of hits were counted to 1232. For the case of strakes, however, the comparison of number of hits is not as relevant, since the threshold for recording of a hit cannot be equally defined in measurements and computations. The comparison between measurements and computations in Fig. 8 show that in the simulations, the hits are predicted to occur over a longer length of the riser than in the measurements. A more concentrated comparison is shown in Fig. 9. The figure shows that the strakes pose an extra challenge to the simulation program. The accuracy is lower than for the cases without strakes. However, it is still seen that the simulations give conservative results

CONCLUSIONS

A coefficient based method for assessing interaction between risers is presented. The method is implemented in the non-linear dynamic finite element tool HYBER. In the present paper, results from the program are compared with model test results. The results are summarized follows:

- The agreement is generally good with a slight over prediction of the collision velocity and collision frequency.
- The length over which hits occur on the riser is predicted conservatively in relation to measurements.
- The number of hits is predicted higher than measured.
- The velocity at hit is predicted with good agreement for bare risers. The velocity at hit is predicted conservatively for risers with strakes.
- For risers with strakes there is a tendency of clinging between the risers when first in touch. This tendency is predicted by the numerical method.

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