FOREWORD

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Amendments and Corrections

This document is valid until superseded by a new revision. Minor amendments and corrections will be published in a separate document normally updated twice per year (April and October).

For a complete listing of the changes, see the “Amendments and Corrections” document located at: http://webshop.dnv.com/global/, under category “Offshore Codes”.

The electronic web-versions of the DNV Offshore Codes will be regularly updated to include these amendments and corrections.
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1. Introduction

1.1 General

A more accurate methodology for assessing riser interference has become increasingly more important when oil and gas exploration moves to deeper water. The risk of interference between marine risers increases with increasing riser length. Historically, the general design practice is that riser collisions are not allowed under normal or even extreme conditions. The present document considers analysis procedures and design criteria for riser interference assessment.

1.2 Objective

The overall objective of this document is to recommend a methodology for engineering analysis, and to provide rational criteria and guidance for assessment of riser interference. Riser interference comprises complex physical phenomena, not yet fully understood, and research is ongoing. The aim herein is to achieve and document the industry consensus as per today.

1.3 Scope and Application

The scope of work is first of all to propose a framework for feasible analysis strategy and practical design procedures with focus on how to assess if the risers collide or not. Whenever the terminology “risers” is used in this document it generally also applies for all types of riser systems e.g. umbilicals, flexible risers, Steel Catenary Risers (SCRs) and Top-Tensioned-Risers (TTRs).

In order to derive a complete framework for feasibility and practical design procedures, the following topics need to be considered:

— overall framework and design approach
— safety philosophy
— environmental conditions and loads
— analysis strategies and hydrodynamic interaction models
— acceptance criteria and fundamental requirements.

The safety philosophy and design principles adopted in DNV-OS-F201 /5/ apply. However, any recognised code considering the set of limit states discussed herein is in principle acceptable. The basic principles are in agreement with recognised codes and reflect state-of-the-art industry practice and latest research.

In view of high uncertainties in interference predictions, no calibration of safety factors is applied. Instead, conservative environmental modelling and analysis are applied; reference is made to DNV-OS-F201 /5/ and API RP 2KD /1/. A formal calibration is neither feasible nor optimal with the present level of experience.

This Recommended Practice formally supports and complies with DNV-OS-F201 /5/. It is recognised to be a supplement to relevant National Rules and Regulations.

1.4 Definitions

**Accidental Loads:** Loads acting on the riser system, due to a sudden, unintended and undesirable event. Typical accidental events have an annual probability of occurrence less than $10^{-2}$.

**Clearance:** Sufficient minimum spacing between risers is documented.

**Coating:** Sheet on the outside of the riser used to protect the riser from damages caused by the surroundings.

**Compliant Configuration:** A unified term for riser/umbilical configurations being a catenary or e.g. free hanging, pliant wave, lazy wave, steep wave, etc.

**Computational Fluid Dynamics (CFD):** Numerical methods which aim to model and solve all physics involved by solving the coupled equations of the structure and the fluid.

**Failure:** An event causing an undesirable condition, e.g. loss of component or system function, or deterioration of functional capability to such an extent that the safety of the unit, personnel or environment is significantly reduced.

**Fatigue:** Cyclic loading causing degradation of the material.

**Force Coefficients:** Non-dimensional coefficients for the drag and lift force as function of relative spacing.

**Global Analysis:** Herein referred to as analysis of forced response of floater and risers due to waves and current.

**Hydrodynamic Interaction:** Interaction effects due to the presence of other structures located nearby in the fluid; e.g., the downstream riser located in the wake of an upstream riser will be affected by the upstream one.

**Impact Angle:** The angle between the relative velocity vector and the line between the cylinder (riser) centres at time and location of impact; also known as kissing angle.

**Impact Event:** One impact event is defined as one collision event governed by the gross riser motion. Each impact event may involve several successive stress peaks, typically 4-5 for a straight hit and 1-2 for a kipping event.

**Impact Velocity:** Referred to as the relative velocity between to colliding risers at the time of impact. Herein denoted as $U_{\text{rel}}$.

**Limit State:** The state beyond which the riser or part of the riser no longer satisfies the requirements laid down to its performance or operation. Examples are structural failure (rupture, local buckling) or operational limitations (stroke or clearance).

**Line Impact:** Assumes the ideal case where the longitudinal pipe axes are parallel at impact.

**Load:** Refers to physical influences which cause stress, strain, deformation, displacement, motion, etc. in the riser.

**Load Effect:** Response or effect of a single load or combination of loads on the structure, such as bending moment, effective tension, stress, strain, deformation, etc.

**Numerical Fluid Flow Models:** Direct force and fluid flow estimation from a CFD solver.

**Operation, Normal Operation:** Conditions that are part of routine (normal) operation of the riser system.

**Point Impact:** Assumes the case where the pipe axes are non-parallel resulting in a small contact area at impact.

**Reduced Velocity:** Non-dimensional velocity parameter used for assessing VIV due to the vortex shedding force.

**Riser Array:** Riser system consisting of vertical or near vertical top-tensioned risers. Typically up to 20 risers distributed in a cluster.

**Riser Interference:** Minimum spacing between risers is less than acceptance criteria.

**Riser Tensioner System:** A device that applies a tension to the riser string while compensating for the relative vertical motion (stroke) between the floater and riser.

**Safety Factors:** Partial safety factors, which transform the lower fractile resistance to a design resistance.

**Screening Analysis:** Used to frame the problem in order to identify if analysis and methods that is more advanced should be employed.

**Side-by-Side Arrangement:** See Figure 1-1

**Staggered Arrangement:** See Figure 1-1

**Strakes:** Helical structural elements attached outside the riser to suppress VIV response.

**Tandem Arrangement:** See Figure 1-1.

**Undisturbed Fluid Flow Model:** Analysis approach disregarding...
ing hydrodynamic interaction effects.

**Vortex Induced Vibrations (VIV):** Resonant vibrations caused by vortex shedding.

**Wake Induced Oscillations (WIO):** Motion of downstream riser due to fluid elastic instabilities when located in the wake of an upstream riser.

**Weight/Diameter Ratio:** Defined as submerged weight per unit length divided by the outer diameter; \( W_s/D \). This ratio may change considerably due to marine growth.

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**1.6 Main Symbols**

- \( C_D \): drag force coefficient
- \( C_L \): lift force coefficient
- \( D \): diameter
- \( E \): Young’s modulus
- \( R_e \): Reynolds number
- \( U_{rel} \): relative impact velocity
- \( V_0 \): free-stream current velocity
- \( V^* \): local inflow velocity
- \( V_d \): wake deficit velocity
- \( V_R \): reduced velocity
- \( V_{WR} \): reduced velocity based upon local inflow velocity in wake
- \( V_{rel} \): relative inflow velocity
- \( V_w \): current velocity in wake
- \( W_s \): submerged weight
- \( \epsilon \): turbulent kinetic energy
- \( \theta \): impact angle
- \( \rho \): fluid (water) density
- \( \Delta \sigma \): stress range
- \( \sigma_y \): Yield stress
- \( \omega \): angular frequency
- \( \omega_n \): fundamental angular frequency

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**1.7 Organisation of Document**

The documents is organised as follows:

Section 2 contains the design approach including design parameters and design principles.

Section 3 provides an introduction to the hydrodynamic interaction phenomenon including wake induced instabilities. Available modelling approaches accounting for hydrodynamic interaction in a global analysis tool are discussed.

Section 4 contains a description and discussion of the procedures and methodologies involved in a riser clearance assessment.

Section 5 contains the basic references used in the document.

Appendix A provides and introduction to the hydrodynamic interaction phenomenon in general. Available methods to estimate the force coefficients applied to describe the hydrodynamic interaction effects have been introduced.

Appendix B provides an introduction to different analysis considerations, such as a description of hydrodynamic interaction models including application areas which are suitable for implementation in a global analysis tool.

Appendix C contains an introduction to local impact stress analysis and requirements regarding modelling issues.

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**2. Design Approach**

**2.1 General**

The individual risers are generally subjected to loading from waves, current and forced wave-frequency and low-frequency floater motions. Whether collision between two adjacent risers will occur or not, depend on many factors such as:

- loading environment
- riser spacing at floater and seafloor terminations
- riser configuration and riser tension
- floater offset involving intact conditions as well as acci-
dental scenarios such as one or multiple mooring line failures:
- marine growth
- hydrodynamic interaction comprising shielding, wake instabilities and VIV
- use of VIV suppression devices, e.g. strakes
- riser operation, e.g. variation in density of conveyed fluids, drilling/completion/workover operations
- accidental load scenarios; e.g. loss of pre-tension or loss of buoyancy
- different static/dynamic properties of the risers due to differences in mass, diameter, effective weight, applied top-tension or effective tension distribution, etc.

Possible riser interference is a key design issue for deepwater floating installations that might be decisive for the choice of floater concept, station-keeping system as well as riser system layout. Riser interference should therefore be addressed in early stages of the design process.

A design target weight/diameter ratio is often specified to achieve similar behaviour of adjacent riser systems. Note that weight/diameter ratio can be significantly influenced by marine growth. This is in particular important for small diameter light weight risers. The design target weight/diameter ratio should hence be checked with and without accounting for marine growth.

2.2 Design Principles

2.2.1 General

Two fundamentally different design strategies apply:
- no collisions allowed
- collisions allowed.

These design philosophies set different requirements to load effect analyses as well as acceptance criteria. Hydrodynamic interaction is a key issue that needs to be adequately accounted for in the load effect analyses for both alternatives. Assessment of structural interaction will in addition be required if collisions between risers are allowed.

The engineering efforts required to qualify a riser system for structural impact is hence substantially more demanding compared to a no collision criterion. However, the cost savings due to relaxation of the no collision design philosophy in extreme and/or accidental loading scenarios may be significant.

Collisions are normally not acceptable in the following scenarios:
- in buoyancy sections for example for compliant configurations
- between risers and mooring lines
- between risers and other structures such as mid water arch and pontoons not specially design for handling contacts
- between risers with unprotected external lines such as kill and choke lines on drilling/workover risers or piggy back umbilicals.

2.2.2 No collision allowed

Sufficient spacing between adjacent risers should be documented for all critical load cases. The load cases should include normal operation, extreme conditions as well as identified accidental scenarios.

Due regard should be given to hydrodynamic interaction in the global load effect analyses.

2.2.3 Collision allowed

Infrequent collision may be allowed provided that the consequences are evaluated and found acceptable. The different loading conditions should be classified depending on probability of occurrence. This means that collisions may be allowed in temporary, accidental and extreme conditions. Collisions in permanent conditions are normally not allowed. It should be documented that the structural integrity is not endangered; i.e. sufficient fatigue and ultimate capacity as well as wear resistance should be ensured.

This should generally be done by combining qualification testing and design calculations.

Static load effect analysis can be used for assessment of the contact load in pure static interference scenarios; e.g. interaction between flexible riser and umbilicals in current conditions with no VIV. Testing may be required in the event that no calculations are available to document that the structures can sustain the contact load considering the local geometry of the contact area.

Please see Appendix C for guidance on local impact analysis, strategy and principles for vertical steel risers.

2.3 Design Parameters for Compliant Configurations

For risers arranged in compliant configurations the following can be considered to mitigate riser interference or reduce the load effects due to contact:
- grouping of risers with similar static/dynamic properties, e.g. weight/diameter ratios
- increased wear resistance by e.g. increased outer sheath in bell mouth, I-J/tube and floater interface area
- design of adjacent system configurations allowing for riser crossing with different vertical positions
- horizontal and vertical staggering of adjacent riser configurations
- separation of the risers with different vertical hang-off angles
- separation of the risers with different azimuth hang-off angles
- cleaning of risers to remove marine growth if necessary
- adjusting the cross-current configuration stiffness by modifying the effective tension through buoyancy and/or weight distribution.

To avoid damage on risers due to mooring line failures it is normally not allowed that a mooring line crosses above the riser in any condition.

2.4 Design Parameters for Top-Tensioned Riser Arrays

TTRs operated from SPAR and TLP platforms are arranged in clusters of vertical- or near vertical risers denoted riser arrays. The number of individual risers in a riser array may be 20 or more.

Top-tension and riser spacing are the primary design parameters to mitigate riser interference. The cost related to increased top-tension and/or riser spacing at floater terminations may be very high. Other proposed design changes to mitigate riser interference or to reduce load effects due to contact are:

1) Grouping of risers with similar static/dynamic properties, e.g. weight/diameter ratios.
2) Cleaning of risers to remove marine growth.
3) Introduction of bumpers or coating along critical areas of the risers to reduce the load effect due to collision.
4) Synchronisation of the tensioners to give equal pay-out or equal effective length for all risers in a riser array.
5) Introduction of spacer frames to keep the risers apart at critical locations.

Operational aspects may limit the applicability of the third approach, while the first and second seem more feasible from that point of view. Further development is needed to establish the last two described alternatives as feasible design strategies.
Conclusions from model tests are that ensuring equal payout for the risers by connecting them to a common frame can be applied to reduce the probability of collision in steady current /14/.

Equal effective length i.e. that the riser length plus the payout length of the tensioner system is equal for all risers, was investigated in /20/.

3. Hydrodynamic Interaction

3.1 General

Assessment of hydrodynamic interaction is a generic issue for load effect analyses related to riser interference evaluations. The importance of the interaction effects is strongly system dependent and should be evaluated on a case by case basis.

Significant effort has been applied to investigate hydrodynamic interaction in steady current; see e.g. the work of Huse /12/ & /13/, Huse & Kleiven /14/ or Kavanagh et al. /16/, while less information is available regarding interaction effects due to wave loading; see e.g. Duggal & Niedzwecki /6/ & /7/.

In addition, numerous experiments to study hydrodynamic interaction for arrays of cylinder sections are performed; for an overview, reference is made to Blevins /2/ and Zdravkovich /33/.

Clashing between SCRs has been investigated by Fontaine et al. /9/. Fernandes et al. /8/ present experiments with flexible jumpers exposed to current. In both cases clashing caused by wake effects were observed. Experimental results on hydrodynamic interaction due to combined loading from waves, current and floater motions seems to be lacking

One may distinguish between three different kinds of physical excitation forces on a downstream riser located in the wake of an upstream riser:

- a broad band buffeting force due to oncoming turbulent flow and vortices shed from the upstream riser, which will induce broad band buffeting vibrations
- a periodic vortex shedding force causing high frequency VIV with limited amplitude
- a time averaged mean force, which varies depending upon the location in the wake.

These loading mechanisms will in general depend on Reynolds number as well as turbulence level in the incoming fluid flow.

Kalleklev et al. /15/ showed that hydrodynamic interaction on the upstream riser conservatively can be ignored, and hence the upstream riser can be treated as an isolated riser. Full attention will therefore be given to hydrodynamic interaction effects on the downstream riser.

As outlined above, the physical load mechanisms on a pair of adjacent risers are complex. The most important effects of relevance for assessment of interaction are:

- reduced mean forces on downstream risers due to shielding effects tending to bring the risers closer
- VIV effects on mean forces on upstream and downstream riser in terms of drag magnification

The non-linear force field generated by the upstream riser may in addition lead to the following hydrodynamic interaction effects:

- wake instability motions of downstream riser
- multiple static equilibrium positions of downstream riser.

The wake instability motions are typically large amplitude motions caused by the position dependent force field due to the upstream riser.

Fundamental research is needed to fully understand these load mechanisms and how they interact with each other. It is therefore required to introduce simplifications supported by rational conservative assumptions in practical riser interference analyses.

3.2 Mean Force in Steady Current

The hydrodynamic loading on downstream riser will be influenced by the wake field generated by upstream riser. The effects on mean forces on the downstream riser are:

- reduced mean drag force due to shielding effects
- lift force due to the velocity gradients in the wake field.

The mean drag and lift coefficients will hence depend on the relative distance between the risers. The mean force coefficients are most conveniently described in a local coordinate system with x-axis in the incoming fluid flow direction, and the y-axis in the transverse direction. The origin is located in the centre of the upstream riser, see Figure 3-1.

Figure 3-1
Coordinate system for description of drag- and lift-coefficients on downstream riser

$V_0$ is defined as the free-stream current velocity which is the velocity on the upstream riser.

Examples of mean drag and lift force coefficients on a cylinder located in the wake of another cylinder of equal diameter are given Figure 3-2 and Figure 3-3 as function of relative spacing between the cylinders. The spacing has been normalised by the diameter of cylinders.

Figure 3-2
Mean drag force on cylinder in a wake [Wu et al. /28/]

-0.20
0.05
0.30
0.55
0.80
1.05
1.30

-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0
$y/D$ [-]

CD [-]

X/D = 2
X/D = 5
X/D = 10
X/D = 15
X/D = 20
X/D = 25
A significant shielding effect is seen when the risers are close. Furthermore, it is seen that the mean lift force is directed towards the wake centre line meaning that it will try to push the riser towards the centre of the wake.

For further details, reference is made to Appendix A and Appendix B.

### 3.3 Drag Amplification due to VIV

Representative drag amplification is based on the estimated VIV amplitude \( A \) normalised by the diameter \( D \). Several expressions for the increase in drag coefficient with vibration exist in literature. The expression presented by Vandiver /25/ is recommended:

\[
C_D' = C_D \left( 1 + 1.043 \left( \frac{2 \sqrt{A}}{D} \right)^{0.65} \right)
\]  

(3.1)

As a conservative estimate, a value slightly on the high side is recommended for the upstream riser. For the downstream riser, it is conservative to apply a lower bound value for the drag amplification due to VIV. This will tend to bring the mean position of the risers closer to each other.

Thus, separate VIV assessments for the upstream- and downstream risers are required prior to the global riser interference analysis. A state-of-practice VIV assessment tool should be applied, see e.g. /23/ or /26/. The upstream riser should conservatively be treated as an isolated riser. The VIV response on the downstream riser should in general be based on the local inflow velocity at a mean position being representative for the VIV response.

Note that very limited information is available regarding VIV behaviour of a riser located in the wake of an upstream one. A conservative lower bound VIV response should therefore be applied for the downstream riser. It is recommended to use no VIV on the downstream riser as a first estimate.

Strakes are commonly used to suppress VIV of risers. In experiments with two adjacent risers, Huse & Kleiven /14/ observed that VIV motions almost disappeared for both risers when attaching strakes. A typical amplitude of one diameter for risers without strakes reduced to one tenth of a diameter for risers with strakes. Also low frequency, stochastic and chaotic motion disappeared.

Another significant observation from the tests was that the risers were kept in mechanical contact after clashing due to changes in the force field.
4. Riser Clearance Assessment

4.1 General

Historically, the design criterion against riser interference typically comprises assessment of the required spacing to avoid collision, see e.g. API RP 2 RD/1.

The first step is to determine whether collisions are likely to occur or not considering floater offset and current loading. At first, the static deflection due to free-stream current loading may be calculated for each riser in the array, neglecting any hydrodynamic interaction between them. If the static deflection is less than the minimum spacing between the risers in nominal static condition, one can for TTRs conclude that riser interference is not a possible scenario and no further analysis is necessary.

Refined analyses taking possible hydrodynamic interaction effects into account is required if the initial assessment reveals that the interaction effects are significant.

4.2 Quasi-Static Analysis

4.2.1 General

The quasi-static analysis should include floater offset and current loading. The omni-directional values for environmental loading and vessel offsets should be applied for all directions from 0 to 360 deg in steps of typically 5-10 deg.

For certain system it can be difficult to assess whether the structures cross or not by looking at the configuration in extreme current. Less severe current conditions may lead to more severe interference scenarios and should hence be considered.

The worst scenario, i.e. combination of floater offset and current loading, should be subject for dynamic analysis accounting for wave loading if required.

Note that possible drag amplification due to VIV needs to be accounted for as described in the previous chapter.

4.2.2 Undisturbed flow analysis

Static analysis of upstream and downstream riser can for undisturbed flow analysis be performed separately. If the results from the undisturbed flow analysis indicate that the hydrodynamic interaction effects are of importance, shielding analysis should be performed.

4.2.3 Shielding analysis

Static analyses using the parametric wake field model for description of hydrodynamic interaction is denoted quasi-static shielding analysis.

Streamlined computations require that the wake field model is implemented in the FE analysis software. However, any computer software for non-linear static analysis of slender structures can be applied using the following iterative scheme for assessment of shielding effects:

1) Compute static upstream riser configuration.
2) Compute static downstream riser configuration under incoming current loading.
3) Compute resulting inflow on downstream riser considering shielding effects from the upstream riser.
4) Re-calculate downstream riser configuration considering resulting inflow as current loading.
5) Repeat steps 3-4 until convergence is achieved.

This approach requires that separate computer models are established for the upstream and downstream risers. The described procedure is a slightly modified version of the approach described by Kavanagh et al./16/.

Shielding effects can in principle be accounted for by modification of the drag coefficient or resulting inflow (i.e. current loading) on the downstream riser. It has however been experienced that modification of current loading on the downstream riser is the most straightforward approach to handle in practical calculations.

4.3 Dynamic Analysis

Simplified assessment of dynamic effects due to waves and floater motions may be based on separate dynamic analyses of the upstream and downstream risers. As an approximation, the converged inflow on the downstream riser (see item 4.2.3) may be applied to represent mean current loading on the downstream riser in such analyses.

4.4 Wake Instability Analysis

Present experience on the wake instability phenomenon from laboratory and field measurements is limited.

Based on available information, wake instability is not considered relevant for compliant configurations. However, it cannot on a general basis be excluded as a possible phenomenon for vertical riser arrays.

Possible wake induced instabilities should be evaluated if the quasi-static shielding analysis reveals hydrodynamic interaction effects along a significant part of the risers.

Dynamic analyses using the parametric mean force model for description of hydrodynamic interaction allows for evaluating possible wake induced instabilities. A tailor-made software application with the parametric mean force model implemented is however required for such analyses. This is because simultaneous dynamic analysis of the upstream and downstream risers is required for application of the parametric mean force.

There is presently no consistent theoretical formulation allowing for combining the parametric mean force model with loading due to waves and floater motions.

4.5 Clearance Acceptance Criterion

Since the parametric wake model is applicable for the far wake region (greater than about two diameters behind the upstream cylinder /16/), the behaviour of the flow in the near wake region cannot be adequately described as it is a highly non-linear phenomenon.
Another issue is that the VIV response of the adjacent risers is not included in the clearance assessment analyses. The maximum VIV displacement can be in the order of one diameter for each riser.

The minimum spacing criterion is selected such that it account for possible VIV on both cylinders. In Figure 4-1, $\Delta$ is defined as the distance between the outside of the cylinders.

With this background, a minimum clearance of two times the outer diameter is recommended for risers with equal outer diameters. The sum of the outer diameters is recommended as acceptance criterion in case of different outer diameters. Hence, to avoid collision the minimum spacing is given by $\Delta \geq D_1 + D_2$. This criterion does not reflect any “safety factor.”

5. References

/1/ API RP 2 RD “Design of Risers for Floating Production Systems (FPSs) and Tension Leg Platforms (TLP’s)”


/5/ DNV-OS-F201 “Dynamic Risers”


APPENDIX A

INTRODUCTION TO HYDRODYNAMIC INTERACTION PHENOMENON

In order to evaluate the fluid-elastic instability and hydrodynamic interaction of the riser pair, an essential prerequisite is the knowledge of the fluid forces on the risers as function of relative distance between the risers.

The first systematic measurements of surface pressure distribution around one of the two parallel cylinders in various staggered arrangements was carried out by Hori /10/. Hori calculated drag and lift coefficients from the surface pressure measurements, and from his results Zdravkovich /30/ plotted the resultant interference force coefficient as shown in Figure A-1. The interference effects are proportional to the vectors shown.

The Reynolds number is defined by:

\[ R_e = \frac{V D}{\nu} \]  \hspace{1cm} (A.1)

where \( V \) is the current velocity, \( D \) is the cylinder diameter and \( \nu \) is the kinematic viscosity.

The Reynolds number for offshore risers with typical diameter of 0.3 m and a current velocity of 1-2 m/s will be between 0.3E + 06 and 0.6E + 06 which corresponds to what is called post-critical or super-critical flow regime, see Figure A-2.

Figure A-2, which is valid for a single cylinder in uniform flow, indicates that the drag force is strongly depending on the flow conditions and the Reynolds number. It is hence expected that the Reynolds number effects are at least equally important for the hydrodynamic interaction in riser arrays as well. For Reynolds number larger than 1.0E + 06, the wake is disorganised and turbulent, which will affect the drag and lift coefficient for the downstream riser significantly.

Most of the experiments and models tests have been performed for low or moderate Reynolds number below the critical regime, but some results have been found in literature considering higher Reynolds number. A few preliminary findings have been reported in the following.

Hori /10/ performed his experiments, which are referred to in Figure A-1, in air with a Reynolds number in the order of 1.0E + 04, i.e. in the sub-critical flow regime. In the post-critical flow regime the wake behind a single cylinder narrows compared with the sub-critical regime /30/. This will cause a similar contraction of the interference boundary in the case of two staggered cylinders.

According to Cooper & Wardlaw /4/ the wake instability boundary moves closer to the upstream cylinder and its wake axis as well.

Figure A-3 shows the lift and drag coefficient variation typical for the sub-critical state of flow measured by Zdravkovich /30/. Figure A-4 shows the lift and drag coefficient variation typical for the post-critical state of flow compiled from the measurements of Wardlaw and Cooper /27/ presented in Zdravkovich /32/. It is observed that the measured forces on the downstream cylinder are almost identical to those in the sub-critical state of flow.

Figure A-1
Interference force coefficients [Zdravkovich /30/]

A direction of the interference force coefficient from right to left indicates that the drag at that position is less than for the single cylinder, while the opposite direction means that the drag is greater than for a single cylinder. The upward direction in the upper half and downward direction in the lower half of the figure indicate a repulsive, positive lift force while the opposite directions in the corresponding halves indicate a negative lift force.

All possible arrangements of the two cylinders are classified into regions by taking into account whether the drag force is greater or less than for the single cylinder and whether the lift force is positive, negative or negligible. The upstream cylinder can be located in three regions:

1) Negligible lift forces and reduced drag forces.
2) Small repulsive lift force and reduced drag force.
3) Repulsive lift force and increased drag force.

The downstream cylinder can be located, in addition to the above three, in the following regions:

4) Negligible lift force and increased drag force. This is a small region and beyond it there is no interference.
5) Negligible lift force and decreased drag force. This is a dominant region for the downstream cylinder.

Note that the above classification is repeated as given in Zdravkovich /30/. In the fifth region, at least the part closest to the wake centre-line and to the upstream cylinder, the lift force should be classified as negative and not negligible. Alternatively, a sixth region could have been introduced in between region one and five with a decrease in drag and an attractive or negative lift force.
Note that the experiments performed for higher Reynolds number e.g. /4/ and /18/ typically in the post-critical flow regime is performed for stranded cables and not for smooth cylinders. Zdravkovich /31/ verified the findings for stranded cables when the flow was simulated by surface roughness around a pair of cylinders.

It is noted from the figures in the Sec.3 that the upstream riser experiences a positive lift force and a reduction in the drag force when being close to the downstream riser. In addition, it is observed that the interaction effects on the upstream riser diminish rapidly when the relative distance between the risers increases. Hence, it will be conservative to ignore the interaction effects on the upstream riser for the purpose of a riser interference assessment.
APPENDIX B

ANALYSIS CONSIDERATIONS

B.1 Strip Formulation

A 2D strip model for the hydrodynamic excitation forces should be applied for the load functions on the 3D risers. Assuming piecewise constant conditions along the riser, conventional strip theory can be applied dividing the two risers into equal number of strips. The strip mesh for the load formulation can be defined relatively coarse. Typically, a coarser mesh than the one applied in order to calculate the global response of the risers can be applied. However, the mesh density should be fine enough to ensure a proper description of the loads acting along the riser.

B.2 Parametric Wake Field Model

A semi-empirical static wake formulation to account for the hydrodynamic interaction between individual risers in steady current was proposed by Huse /11/, /12/ & /13/. The parametric wake field formulation is based on the turbulent wake expressions of Schlichting /22/. The deficit velocity field in the wake of a circular cylinder is given by:

\[ V_d(x, y) = k_2 V_0 \left( \frac{C_D D}{x_s} \right)^{0.09} \left( \frac{x}{x_s} \right)^4 \]  
(B.1)

where \( x_s \) and \( b \) are defined as

\[ x_s = x + \frac{4D}{C_D} \]  
(B.2)

\[ b = k_1 \sqrt{C_D D x_s} \]

The deficit velocity field \( V_d(x, y) \) is described in a local \( xy \) co-ordinate system with \( x \)-axis in the current direction and origin in centre of the cylinder. The other parameters involved are:

- \( D \)- cylinder diameter
- \( V_0 \)- free-stream current velocity
- \( C_D \)- drag coefficient
- \( k_1, k_2 \)- empirical constants

where \( k_1 = 0.25 \) and \( k_2 = 1.0 \) for a smooth cylinder. The resulting inflow on a downstream riser at position \((x_1, y_2)\) is hence given by:

\[ V_{in} = V_0 - V_d \]  
(B.3)

This principle has been extended to multiple riser arrays by Huse /12/, who proposed a scheme for calculation of resulting inflow on a riser influenced by the wakes of several upstream risers.

The inflow velocities and wake fields for all upstream risers are computed sequentially in current flow direction starting with the far upstream riser. Based upon correlation with experiments Huse /12/ recommends to apply RMS (Root Mean Square) summation of the individual wake fields from all upstream risers. The inflow on a downstream riser at position \((x_1, y_2)\) is hence given by:

\[ V_{in} = V_0 - V_d \]  
(B.3)

This principle has been extended to multiple riser arrays by Huse /12/, who proposed a scheme for calculation of resulting inflow on a riser influenced by the wakes of several upstream risers.

The main advantages of the parametric wake field model are:

- it allows for assessment of shielding effects in steady current without making use of dedicated software.

The main limitations of the model may be summarised as:

- the formulation is static, which means that the model is not applicable for prediction of impact velocity and collision intensity;
- the turbulent wake model is applicable to the far wake field only, i.e. the model is not considered valid when the relative distance between adjacent risers is less than two diameters, and
- the load formulation does not include a lift force formulation which is considered essential for describing the instabilities in the wake. Note that in recent studies Blevins /3/ has included a lift force formulation.

B.3 Parametric Mean Force Model

A parametric force model requires that the force coefficients are derived as functions of relative riser spacing. The drag and lift coefficients should be established by model tests or 2D numerical calculations (e.g. CFD) for the actual cross-sectional configurations. The dynamic formulation outlined below is applicable to two-riser systems in steady current. The co-ordinate system applied in the load formulation and the configuration of two cylinder sections in steady current are given in Figure B-1.

\[ \gamma \]

**Figure B-1**

Time-averaged properties of the turbulent wake of a cylinder with a downstream cylinder in the wake

\( V_0 \) is the free-stream current velocity and i.e. inflow velocity on the upstream riser. The inflow velocity on the downstream riser, \( V_{in} \), is adjusted due to shielding effects e.g. by making use of the generic drag coefficient approach as described below or the parametric wake field model outlined in the section above. The \( x \)-coordinate is taken as the longitudinal direction with respect to the incoming fluid flow, and the \( y \)-coordinate in the transverse direction. The origin is located in the centre of the upstream riser.

A parametric representation of the hydrodynamic loading on two-riser systems, which has gained consensus throughout the literature, is derived in e.g. Blevins /2/. The time averaged mean fluid forces on the downstream cylinder may be described by:

\[ F_x = F_D \cos \gamma - F_L \sin \gamma \]

\[ = \frac{1}{2} \rho V_0^2 D \left( C_D \cos \gamma - \overline{C}_D \sin \gamma \right) \]  
(B.4)

\[ F_y = F_D \sin \gamma + F_L \cos \gamma \]

\[ = \frac{1}{2} \rho V_0^2 D \left( C_D \sin \gamma + \overline{C}_D \cos \gamma \right) \]

where \( r \) is the fluid density, \( C_D \) an \( \overline{C}_D \) are the local mean drag...
and lift coefficients. The other parameters are defined in the force diagram shown in Figure B-2.

\[
V_{rel} = \sqrt{(V^{*} - \hat{x})^2 + \hat{y}^2} \quad \text{(B.5)}
\]

where \( \hat{x} \) and \( \hat{y} \) are the structural velocity in \( x \)- and \( y \)-directions, and \( V^{*} \) is the local inflow velocity. The local inflow velocity \( V^{*} \) is defined as the free-stream current velocity \( V_0 \) for the upstream riser and for the downstream riser as the local wake velocity \( V_w \) after accounting for shielding effects. Per definition the local inflow velocity is parallel to the \( x \)-axis. In the following \( V^{*} \) is used as the local inflow velocity to indicate that the relations yields for both the upstream and downstream risers. \( V_0 \) or \( V_w \) will be used when the relations yields for upstream or downstream riser only.

From the force diagram the following relations can be outlined:

\[
\cos \gamma = \frac{V^{*} - \hat{x}}{V_{rel}} \quad \text{(B.6)}
\]

Further, the mean drag and lift coefficients for the downstream riser can be related to the free-stream velocity \( V_0 \) by:

\[
C_D = \frac{\bar{C}_D}{V_0^2} V_w^2 \quad ; \quad C_L = \frac{\bar{C}_L}{V_0^2} V_w^2 \quad \text{(B.7)}
\]

and the fluid forces may be rewritten as:

\[
F_x = \frac{1}{2} \rho V_{rel} D \frac{V_w^2}{V_0^2} (C_D (V_w - \hat{x}) + C_L \hat{y})
\]

\[
F_y = \frac{1}{2} \rho V_{rel} D \frac{V_w^2}{V_0^2} (-C_D \hat{y} + C_L (V_w - \hat{x})) \quad \text{(B.8)}
\]

The force coefficients are tabulated as functions of relative spacing between upstream and downstream riser, \( C_D(x,y) \) and \( C_L(x,y) \).

The local inflow velocity in the wake is needed in order to calculate \( V_{rel} \) for the downstream riser. It might be estimated using the approach of Price & Piperni /19/:

\[
V_{rel}(x,y) = V_0 \sqrt{\frac{C_D(x,y)}{C_{DG}}} \quad \text{(B.9)}
\]

where \( C_{DG} \) is a generic drag coefficient and \( C_D(x,y) \) is the drag coefficient of the downstream cylinder influenced by the wake. The main advantages of the parametric mean force model are:

- the formulation is simple to implement in standard FE riser analysis tools, and it allows for arbitrary depth variation of the current loading along the riser
- the instantaneous hydrodynamic loading on the individual risers is expressed by a parametric formulation as function of relative position of the adjacent riser
- the formulation allows for re-use of results from advanced CFD calculations and/or model tests in practical design analyses. With a comprehensive database, it is possible to cover a wide range of two-riser systems
- the effects from strakes or other VIV suppression devices may be included by means of results from model tests, and
- the load formulation has gained consensus throughout most of the literature.

The main limitations of the model may be summarised as:

- the formulation is impractical for extension to multiple riser arrays or more complex load cases (e.g. WF excitation)
- the force coefficients depend on Reynolds number, i.e. it is necessary to obtain databases for a range of Reynolds number.

### B.4 Estimating the Force Coefficients

The force coefficients applied to describe the hydrodynamic interaction effect between a pair of risers can be derived from e.g. dedicated CFD analysis or laboratory tests or from other numerical methods such as the free-streamline method.

It is generally necessary to establish a database of the mean drag and lift forces on the downstream cylinder as function of relative spacing from the upstream one.

Figure B-3 shows typical locations of the downstream riser where the upstream cylinder is located in the origin, \( x \)-axis points longitudinal in the current direction and \( y \)-axis transversely to the current direction. The downstream cylinder is located at different locations in the wake of the upstream one. In this illustrative example, the force coefficients are established for 28 different arrangement.

Note that both the drag and lift force are symmetric around the wake centreline, and it is only necessary to estimate the coefficient on one side. Generally, the mesh should be denser for smaller spacing where the hydrodynamic interaction effects are most pronounced. As illustrated the mesh can be coarser farther out and down in the wake.

In between the locations given in the database, the force coefficients are based upon either linear or more advanced interpolation. It is recommended to apply linear interpolation for two reasons:
— the gross riser displacement is assumed unaffected by local variations
— uncertainties of each of the known values are quite significant; e.g. it depends on the level of accuracy when estimating it, but also on the Reynolds number, roughness etc.

It is generally recommended that the force coefficients should be estimated from the wake centreline and 4 diameters in transverse direction. In longitudinal direction, typically 20 to 25 diameters should be sufficient as an upper boundary. The force coefficient should also be estimated with as low spacing as possible, e.g. a lower boundary of 1.5-2 diameters centre-to-centre distance should be applied.
APPENDIX C
LOCAL IMPACT STRESS ANALYSIS OF STEEL PIPES

C.1 General

Local non-linear dynamic analyses should be performed in order to capture the local dynamics of the riser at an impact. The result of the analyses should be the peak stresses, stress ranges and typically number of stress peaks in one collision event. The analysis should be performed for a range of different relative impact velocities and impact angles, /15/.

The resulting load effects further depend on the pipe-wall deformation properties. The “participating mass”, see e.g. Li & Morrison /17/, depend strongly on the impact duration and will normally be implicit in the solution and not an input-parameter.

The strategy for calculation of the collision induced load effects depend on the type of impact, such as:

— line impact
— point impact.

In addition, the effect of coating and strakes should be considered if relevant. Coating is effective in reducing the stresses even for small thickness’ typical for corrosion protection. The reduction in stresses in the pipe due to the coating is reduced with an increasing stiffness of the coating.

The peak stresses and stress-ranges for one specific impact need to be determined based on detailed finite element analysis. The response can be strongly dominated by local dynamics, and a quasi-static approach is in general not sufficient.

C.2 Response Surface

Based on finite elements analysis, a response surface for stress component $s$ may be derived as function of relative impact velocity and impact angle as follows:

$$\Delta \sigma(U_{rel,n}, \theta)$$  \hspace{1cm} (C.1)

The form of the response surface will typically take the shape of a 2nd order polynomial in the plane of impact angle and stress response. The plane of impact velocity and stress response, the relation will be approximately linear. Figure C-1 shows a response surface plotted in a 3D diagram.

For determining this response surface, a series of finite element analyses need to be carried out. The analyses can be limited to series of analyses with given impact velocity for three different impact angles. A 2nd order curve through these three points can then be established.

C.3 Requirements to Finite Element Model

The extent of the 3-D element model should be large enough such that the local dynamics giving the peak stresses is not impaired by boundary conditions. Generally, a half joint, applying symmetry conditions, will be sufficient.

The type of element should either be shell or solid volume elements with contact modelling between the impacting surfaces, see Figure C-2.

The mesh density should be fine enough to capture the local dynamics as well as giving the proper measure for the shell bending stresses in the pipe wall. Generally, sensitivity analyses should be performed in order to verify the model.

Contact modelling should be made with a method, which implies little sensitivity to the peak stresses. A Lagrange multiplier technique meets this criterion, as this solves the equation defining no intrusion between the two contacting surfaces. Other methods, like the “penalty stiffness” method may be applied if the selected contact spring stiffness is documented to yield satisfactory contact stresses.

A conservative approach for mass modelling is to apply the entire mass as an equivalent mass to the outer cross-section. More detailed and less conservative way of applying the masses may be done as long as they are properly documented.

The time stepping procedure needs to be sufficient small to provide reliable results for the peak stresses. Typically, the rise time for the peak stresses at the area of impact is in the order of 1 millisecond.

A convergence study should be performed in order to evaluate the expected accuracy of the results in the applied model. This type of time-domain non-linear dynamics are fairly time consuming, the mesh density needs for practical purposes to be limited to a level that gives satisfactory results.

Generally, the models should be run with a refinement in all directions. Examples of this are shown in Figure C-3, starting with fairly coarse meshes, and gradually refining the meshes in longitudinal and circumferential directions.
C.4 Special Case Impact

As a special case, the riser-riser line impact problem assumes that the risers are effectively impacting in a straight, parallel and co-planar configuration. The derivation assumes a simplified analytical ring model as follows:

- the two risers may be considered as a simple mass-spring-mass system
- the assessment can be based on elastic ring and beam theories
- the impact force is assumed to act as a point load
- linear elastic response may be assumed for the vast majority of realistic line-like collisions.

The required input to the analyses is as follows:

- mass per unit length incl. added mass for the risers, i.e. $m_1$ and $m_2$
- mean diameter $\bar{D}$ and wall thickness $t$ for the risers;
- combined contact stiffness $k_c$ representing the cross-sectional force-deformation characteristics of the risers during the impact, and
- relative velocity of risers prior to the impact $U_{rel}$.

According to assumption 1, the impact force per unit length $p$ is given by; see e.g. Li & Morrison /17/:

$$ p = \sqrt{k_c \frac{m_1 m_2}{m_1 + m_2} U_{rel}} \quad (C.2) $$

The contact stiffness $k_c$ may be evaluated directly from assumption 2 & 3.

$$ k_c = \frac{2}{3} \frac{32\pi}{3(3\pi - 8)} \left( \frac{D_1}{t_1} \right)^3 + \left( \frac{D_2}{t_2} \right)^3 \right)^{-1} \quad (C.3) $$

Where $\bar{D}$ is the mean diameter, $E$ is Young’s modulus and indices 1 and 2 indicating riser 1 and riser 2.

The pipe wall stress may be evaluated using the following expression:

$$ \sigma = C \left( \frac{p}{t} \right) \left( \frac{D}{t} \right) \quad (C.4) $$

where $C$ is a correction factor accounting for the ring thickness. $C \approx 0.7$ applies for the mid-wall and should be used for fatigue purposes and $C \approx 0.74-0.80$ corresponds to the maximum tensile inner fibre stress at the ring.