Innovative 3-D Implementation of Riser Wake Interference Assessment

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ABSTRACT

As the water depth of field developments increases, the risers systems (SCR's, Flexibles, single HRT's or bundle-HRT's) follow parallel courses. Several recent experimental works (Blevins, et al., 2006 & 2007) have shown the significant length over which the lift and drag on a downstream cylinder is influenced by the wake of an upstream cylinder. However, current industry practice does not include the lift force contribution when assessing the riser wake interference. Both effects are considered – the drag reduction on a downstream riser due to it being in the wake of an upstream riser, and the lift force on the downstream riser towards the center of the wake of the upstream riser.

Several phases of model tests have been performed at the Scripps Institution of Oceanography. The paper provides details of the experimental set-up and main results. The tests were conducted at a Reynolds number of about 80 000. Conclusions are drawn on the possibility of extending the theoretical model (to include both the lift and drag) to cover VIV.

The paper also presents work to implement numerical models of wake interference in a riser analysis program. This work generalizes 2D theoretical models and test results to 3D modeling of real riser systems.

KEY WORDS

Riser Wake Interference, HRT, SCR, Lift Force, VIV, FPSO.

INTRODUCTION

As the water depth of oil & gas exploration is getting deeper and deeper, production risers become a critical component of field developments. Parallel risers are attached to these deepwater floating production units, such as Semi-submersible (Semi), Tension Leg Platform (TLP), Spars as well as Floating Production Storage and Offloading (FPSO). FPSOs are increasing popular worldwide; there will be two Turreted-Moored FPSO systems installed in the Gulf of Mexico (GOM) in the next few years.

The major types of deepwater risers are flexibles, Hybrid Riser Towers (HRTs) and Steel Catenary Risers (SCRs). Three HRT's (Figure 1) have been successfully in service with spread moored FPSO vessels in West Africa (WA) since 2001 on the Girassol Project. Two more HRTs have been also installed in WA lately. Besides being field proven, Hybrid Riser Towers offer the below specific advantages:

- Large diameter risers can be accommodated
- In-place riser fatigue is low
- Field layout is simplified and allows future expansion
- Demanding flow assurance requirements can be met
- Riser hang-off loads on the Floating Production Unit are drastically reduced

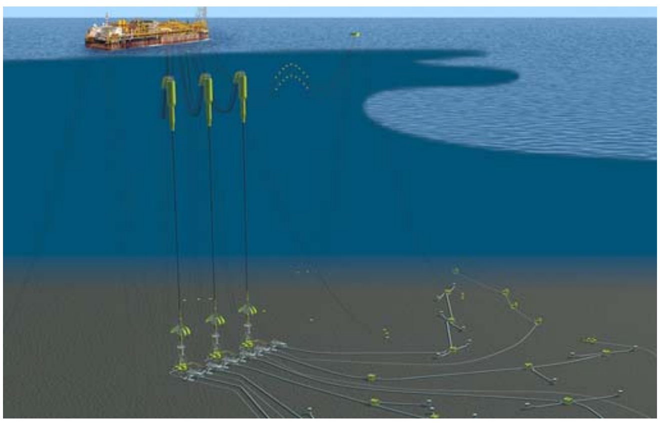

Figure 1: Riser Tower Systems installed at West Africa

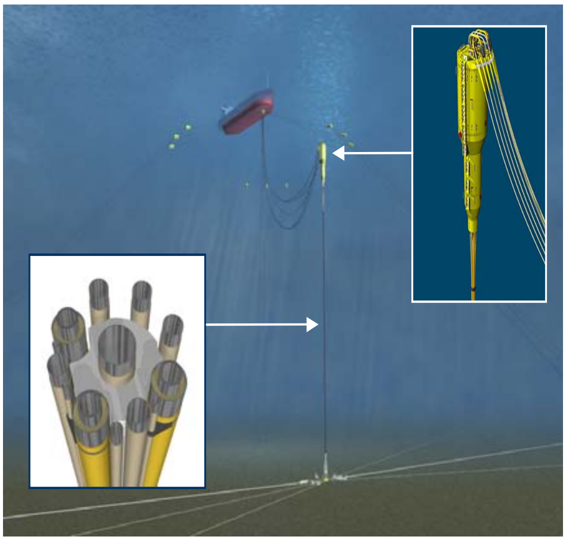

Figure 2: Multiple jumpers attaching to a Turret-Moored FPSO

Meteocean conditions in West Africa (WA) allow the use of spread mooring. This may not be the case for other areas of deepwater production. In the Gulf of Mexico, for example, the extreme meteocean conditions (100-year storm and 100-year hurricane conditions, the Loop Current, eddy currents, and submerged currents), and the size of the FPSO (AFRAMAX), require a turret-moored FPSO with jumpers running between the HRT and the rotating turret, as shown in Figure 2. In Brazil, the environment is generally between GOM and WA, so is the requirement for riser design.

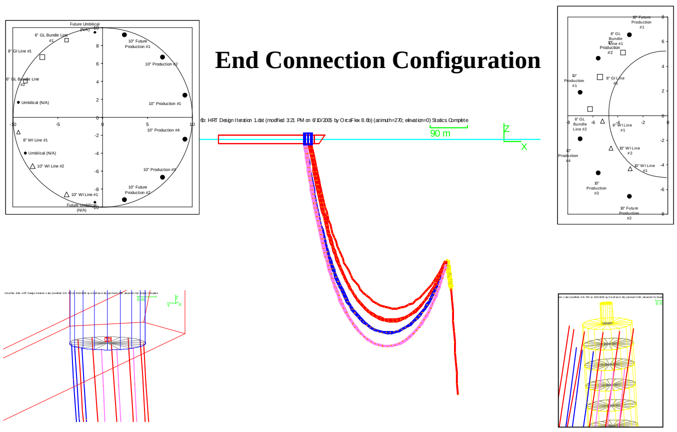

Figure 3: Jumper Hang off Point Design to avoid riser clashing

In one GOM deepwater field development study case, as shown in Figure 3, the hybrid riser tower consists of a riser bundle, a submerged buoyancy tank and flexible jumpers between the buoyancy tank and the FPSO. Up to twelve jumpers hang in catenaries between the pivoting turret on the underside of the FPSO hull and the buoyancy tank that is about 200 m below sea level. The jumpers are closely spaced and it is therefore possible that the downstream jumpers can fall into the wake of the upstream jumpers when responding to environmental loads from waves and currents. Wake interference reduces the drag on the downstream jumpers. Combining with the effect of lift force, which could draw the downstream jumper onto the wake of the upstream jumper, it would increase the potential for jumper clashing. Consequently, two particular aspects of wake interference, wake shielding and wake instability, must be investigated. However, current industry practice does not include the lift force contribution when assessing the riser wake interference.

ANALYTICAL APPROACH

The full assessment of wake shielding and wake instability requires a model that accounts for both lift and drag forces. Whereas drag effect based on Huse model (Huse, 1993) is well documented in DNV, no methodology was available for lift. Blevins published a model including lift (Blevins, 2005), as illustrated in Figure 4.

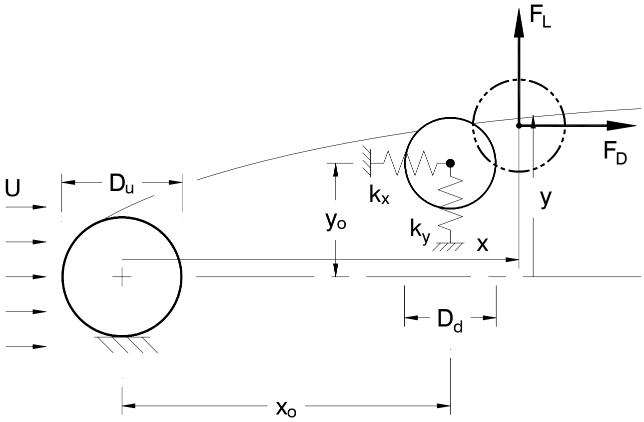

Figure 4: Fixed upstream cylinder and spring-supported downstream cylinder

The theory of Blevins, is applied to predict the response of the downstream cylinder, combining the effects of both drag and lift forces. These predict that within the confines of the wake of the upstream cylinder, the drag on the downstream cylinder is reduced and there is a lift force that acts to draw the downstream cylinder into the wake of the upstream cylinder.

The major difference between the Huse and Blevins theories is that the later has a lift force that attracts the wake cylinder to the upstream cylinder. As a result of lift, the Blevins theory is always more conservative than Huse theory for cylinder clashing predictions. In the far wake the two give similar results, but in the near wake where velocity gradients and lift are large the theory with lift will predict an observed clashing, as shown in Fig. 8, where the theory without lift will not.

The equilibrium position of a downstream cylinder subject to lift and drag is provided in the Appendix.

A full assessment of interference was then carried out for jumper lines between an HRT and FPSO turret in GOM that included a methodology for the evaluation of wake shielding and wake instability. The results of the jumper interface assessment confirmed the applicability of the Hybrid Riser Tower system with a turret-moored FPSO in the Gulf of Mexico, as depicted in Figure 3.

These results, presented at ISOPE 2006 (Blevins, et al., 2006) used the relatively low Reynolds number (20,000) data available in the literature. From these, a methodology to be able to incorporate the findings in the design of risers and field layout, was presented at DOT 2006 (Blevins et al., 2007).

Blevins (2005) introduced "critical curves" for the boundary of the occurrence of significant wake instability. Figure 5 shows the comparison of this criterion for wake interaction with direct integration of equations for an 8-inch upstream cylinder and 6 inch downstream cylinder at four initial positions.

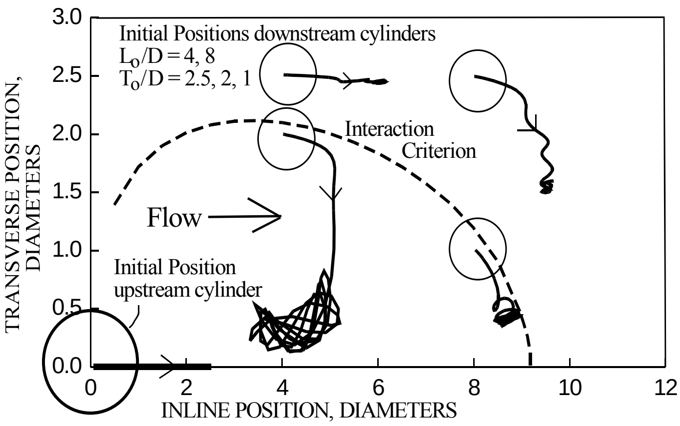

Figure 5: Critical curve for wake instability.

EXPERIMENTAL CONFIRMATION

To experimentally confirm the above analytical results, in 2006 Acergy funded a higher Reynolds number (80,000) hydrodynamic experimental investigation at the Scripps Institution of Oceanography in San Diego. In the 2006 experiments, as shown in Figures 6 & 7, the upstream cylinder is held fixed, while the downstream cylinder was free to move in both directions. The experimental data and the analytical comparison with theory were presented at OTC 2007 (Blevins, Wu, 2007).

The flow channel has a 1.12 m (44 inch) wide by 1.13 m (44.4 inch) deep section and a working test section length of 16 m (52.5 ft) with glass on both sides for photography. Flow velocities can be varied from 0.15 to 1.25 m/s (0.49 to 4.1 ft/s). The upstream and downstream cylinders are 6.35 cm (2.5 inch) outside diameter aluminum tubes. Their surface was sanded with 220 grit sand paper to give a roughness of approximately 30 micro inch average (Ra), or e/D= 10 x10^{-5}. Because the experiments are in Reynolds number range where cylinder drag and vortex shedding are stable and predictable, it is believed that the results are conservative for higher Reynolds number in the 1 million range where drag drops and vortex shedding is less organized.

The experiments were performed to validate the parameters of the theoretical models. The measurements confirm that "as the flow increases, the downstream cylinder travels aft and inward towards the centerline of the wake". At small inline spacing, the downstream cylinder moves upstream, implies negative drag, and impacts the fixed upstream cylinder.

Figure 6: Scripps Institution of Oceanography, Flow Channel and test set-up

Figure 7: Side view of Stratified Flow Channel. The vertical cylinder is the test cylinder.

The test results, in Figure 8, for downstream cylinder static motions validate the theory for fluid forces in the wake on an elastically supported cylinder.

It can be observed from Fig.8 that:

- outside of the wake (such as at L/D=4 and T/D=1), the cylinder remains on a line parallel to the axis of the flow proving that there is no lift
- inside of the wake area of influence the large inward movement of the downstream cylinder can only be attributed to the lift

The results also show that incorporation of the lift force is required to obtain results that compare well with observed data.

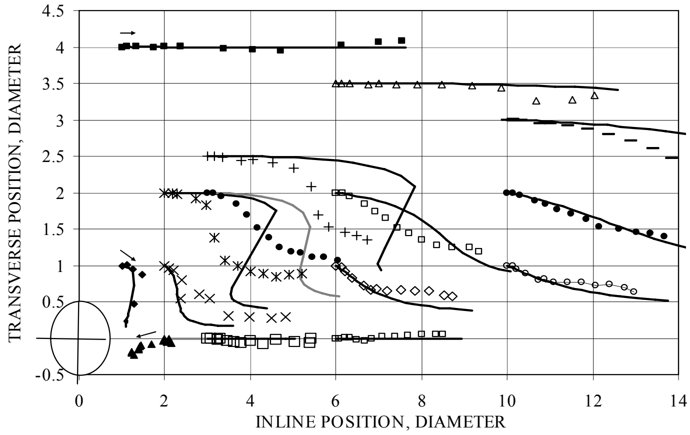

Figure 8: Comparison of predicted (solid lines) and experiment (data points) with increasing velocity. Fifteen tests were made with the following initial inline and transverse positions of the center of the downstream cylinder relative to the center of the upstream cylinder, in diameters: (1,1), (2,0), (2,1), (2, 2.), (3,0), (3,2), (3, 2.5), (6,0), (6,1), (6,2), (6,3.5), (10,0), (10,1), (10,2), (10,3).

A separate set of experiments were performed to investigate the length of exposure (Blevins, Saint-Marcoux, 2007).

NUMERICAL IMPLEMENTATION IN 3D

Models of wake interference such as the Huse and Blevins models are 2D models that cover the simple situation of a pair of parallel rigid cylinders in flow normal to their axes. Some generalization is needed to apply such models to real engineering analysis and design work.

For example real risers have curvature and in analysis work they are modeled in 3D using a number of finite elements to represent each riser. Each element can be considered to be like a small cylinder, but a given element can in general be in any position and orientation relative to other elements in the model. Also, a given downstream element might be in the wake region of more than one upstream element at any given time. And it might move from the wake region of one upstream element to the wake of a different one as the system moves. Because of this, to apply the 2D models in 3D analysis programs requires some generalization from 2D to 3D, and also rules for deciding which upstream riser element(s) generate wake that affects any given downstream riser element.

These generalization issues have been addressed as part of implementing wake interference modeling in a riser analysis program (Orcina, 2008). In the program the user can choose between the Huse or Blevins model. Or the user can choose to specify the wake model numerically, in the form of a table of wake drag and lift coefficients as a function of the downstream element position relative to the upstream element wake.

Consider the scenario illustrated in Figure 9 below, where a given downstream riser element moves relative to the upstream riser elements. As the downstream element moves from the wake of one upstream element to another, the transition needs to be modeled in a way that is continuous, i.e. gives drag and lift forces that are continuous functions of the position of the downstream element relative to the upstream elements. This continuity requirement is important in numerical analysis programs, since in order to calculate the mean static position of the system, or do a time integration of its dynamic response, such programs need to solve static or dynamic equilibrium equations, and those equations might have no solution if the drag or lift forces are discontinuous functions of the positions of the elements in the model.

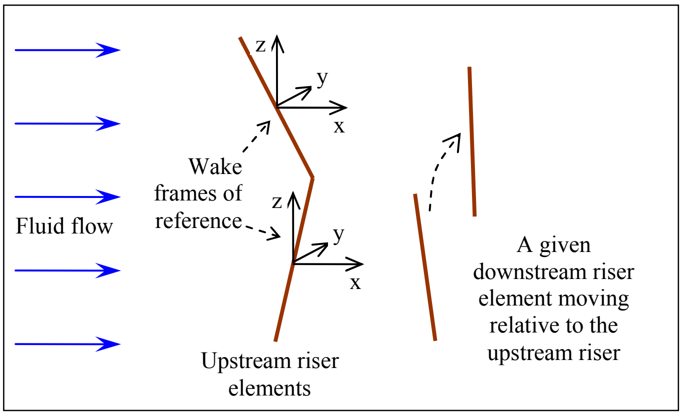

Figure 9: Example of the more general configurations that need to be modeled.

To apply these 2D models in 3D, each upstream element is first given a wake frame of reference, whose origin is at the upstream element's centre. The wake frame x-axis is the in-line direction, i.e. the direction of the fluid velocity vector at the upstream element. The wake frame y-axis is the transverse direction, i.e. the direction normal to the plane formed by the upstream element axis and the fluid velocity vector. The wake frame z-direction is the direction obtained by projecting the upstream element axial direction normal to the flow direction, and this completes an orthogonal right hand triad of wake axes x,y,z.

These wake frames of reference are then used to calculate the wake effects on a given downstream element. Firstly, the program considers each possible upstream element and calculates the downstream element's (x,y,z) position relative to that upstream element's wake frame of reference. The x and y-coordinates are then used then as the inputs to the chosen 2D wake model, and this gives the wake effect that upstream element would have if there was no axial displacement between the two elements.

Clearly the z-coordinate needs to be taken into account, so a z-dependent scaling factor is then applied. The factor is 1 when z is small and scales down to zero when the downstream element z position takes it significantly beyond the ends of that upstream element. When this occurs the downstream element is now fully in the wake region of the neighboring upstream element, i.e. the next element along in the finite element model of the upstream riser. And the scaling factor algorithm is arranged to give overlap, i.e. so that as the downstream element moves from the wake region of one upstream element to that of its neighbor then the scaling factor applied to the neighbor's wake effects has already reached 1 before the scaling factor applied to the first element's wake effects is reduced below 1.

The program has now calculated scaled wake effects on the given downstream cylinder from each of the possible upstream elements. In the scenario shown in Figure 9 both upstream elements can give non-zero scaled wake effects, but only one should be applied, since the upstream elements model consecutive elements of a single upstream riser. The program then selects and applies only the wake effect of the upstream element that gives the largest scaled wake effect at any given time. Choosing the upstream element that gives the largest wake effect gives a continuous handover from one upstream element to the next as the downstream element moves from the wake region of one upstream element to the wake region of the next. And the scaling factor overlap described above ensures that the wake effects are not wrongly scaled down as the handover occurs.

RESULTS: VALIDATION OF THE IMPLEMENTED MODEL IN A 2D SITUATION

Trials of this 3D implementation of wake interference have been performed and show promising results. The numerical implementation was first tested for the simple 2D situation of a spring-mounted rigid cylinder in the wake of a fixed rigid cylinder, and this successfully reproduced the results of Blevins and Wu (2007). This is illustrated by Figure 10, which shows the program results compared to the experimental results, for one case of the Scripps experiments given in the above OTC paper.

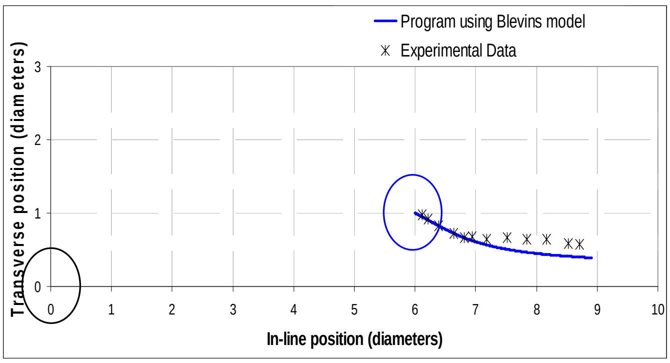

Figure 10: Comparison of program results using Blevins model results and Scripps experiment results, for undistributed position 6 diameters downstream and 1 diameter transverse.

For the case shown in Figure 10, when the current velocity is slowly reduced back to zero, the downstream cylinder retraced its path back to its undisturbed position. For another case (2 diameters downstream, 2 diameters transverse) the return path did not exactly follow the 'outward' path, showing signs of the dynamic instability documented by Blevins (2005).

RESULTS: IMPLEMENTATION IN 3D COMPARISON WITH TRADITIONAL RESULTS

The software was applied to a configuration similar in nature to that of Figure 3 for jumpers from a Hybrid Riser Tower to an FPSO.
The interference analysis was conducted under three conditions:

- no wake effect
- drag effect only (wake shielding) per Huse model (Huse, 1993 & 1996)
- drag and lift effect (wake shielding and potential wake instability) per Blevins model (Blevins, 2005)

The resulting clearance between two jumpers is shown in Figure 11. It can be observed that, as recommended by DNV-RP-F203, it is un-conservative to neglect the effect of lift

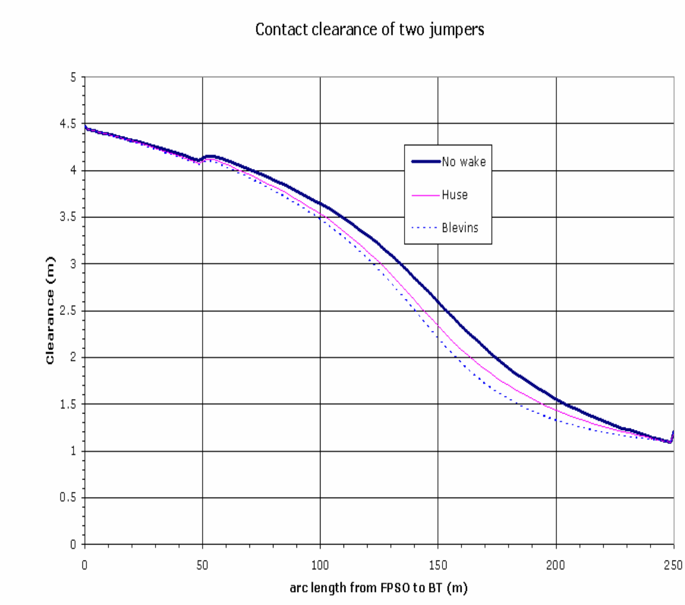

Figure 11: Clearance between two jumpers along their arc length from the FPSO to the Buoyancy Tank

CONCLUSION

Measurements have been made of the motions of an elastic cylinder in the wake of a full and partial upstream fixed cylinder. The tests confirm the existence of an inward lift force on the cylinder is in the wake and reduced drag. This work has practical implications in the design of deepwater riser and jumper systems as it allows evaluating proposed riser and jumper systems in congested areas.

The Blevins model has been incorporated in a riser analysis program. The software has been validated by comparing with the experimental results in 2-D. In addition the 2-D model has been extended to 3-D configurations tractable by the software.

Applications to actual engineering configurations confirm that the effects of wake shielding and wake instability mentioned in DNV-RP-F203 are significant and now tractable in the context of a project.

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APPENDIX : THEORY – EQUILIBRIUM POSITION

The forces acting on the downstream cylinder are the stiffness in the x and y directions, which are respectively balanced by the drag and lift:

$$k_x(x-x_0)=\frac{1}{2}\rho U^2 D_d F_D(x,y)$$

$$k_y(y-y_0)=\frac{1}{2}\rho U^2 D_d F_L(x,y)$$

Introducing:

$$q=\frac{1}{2}\rho U^2$$

$$\xi=\frac{qC_{Dd0}}{k_x}$$

Where q is the dynamic pressure and ξ is the dimensionless measure of the drag force relative to the spring stiffness (Cauchy number). The ratio ξ may also be expressed in term of the natural frequency of the spring in the longitudinal direction:

$$\xi=\frac{1}{8\pi^2}\frac{\rho D_d^2}{m}\left(\frac{U}{f_x D_d}\right)^2 C_{Dd0}$$

Where $f_x=\frac{1}{2\pi}\sqrt{\frac{k_x}{m}}$, Hz

The lift and drag equations can be written

$$x-x_0=\xi D_d\frac{F_D(x,y)}{C_{Dd0}}$$

$$y-y_0=\frac{k_x}{k_y}\xi D_d\frac{F_L(x,y)}{C_{Dd0}}$$

Expressing the drag and lift in term of the exposure leads to:

$$x-x_0=\xi D_d(\varepsilon\frac{C_D(x,y)}{C_{Dd0}}+(1-\varepsilon))$$

$$y-y_0=\frac{k_x}{k_y}\xi D_d\varepsilon\frac{C_L(x,y)}{C_{Dd0}}$$

Including the expression for the drag in the equation for x

provides:

$$x-x_0=\xi D_d(\varepsilon\cdot\left(1-a_1\cdot\sqrt{\frac{C_{Du0}\cdot D_u}{x}}\cdot e^{-\frac{a_2\cdot y^2}{C_{Du0}\cdot D_u\cdot x}}\right)^2+(1-\varepsilon))$$

which can be re-written as:

$$(\frac{x-x_0-(1-\varepsilon)\xi D_d}{\varepsilon\xi D_d})^{\frac{1}{2}}=1-a_1\cdot\sqrt{\frac{C_{Du0}\cdot D_u}{x}}\cdot e^{-\frac{a_2\cdot y^2}{C_{Du0}\cdot D_u\cdot x}}$$

The lift coefficient is given by:

$$C_L(x,y)=a_3\cdot\left(\frac{C_{Dd0}\cdot D_d\cdot y}{C_{Du0}\cdot D_u\cdot x}\right)\left(1-a_1\cdot\sqrt{\frac{C_{Du0}\cdot D_u}{x}}\cdot e^{\frac{a_2\cdot y^2}{Cd_{Du}\cdot D_u\cdot x}}\right)\cdot\sqrt{\frac{C_{Du0}\cdot D_u}{x}}e^{\frac{\cdot a_2\cdot y^2}{C_{Du0}\cdot D_u\cdot x}}$$

and is introduced in the equation for the transverse zero-force position as follows.

$$\frac{y}{D_d}-\frac{y_0}{D_d}=\frac{y}{D_d}\frac{\varepsilon a_3 k_x D_d^2}{a_1 C_{Du0}k_y D_u x}(\xi^{\frac{1}{2}}(\frac{x-x_0-(1-\varepsilon)\xi D_d}{\varepsilon D_d})^{\frac{1}{2}}-(\frac{x-x_0-(1-\varepsilon)\xi D_d}{\varepsilon D_d}))$$