Current Forces on Net Structures

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Abstract

A simplified flow model for a net structure is presented. The net is divided into cylindrical elements, representing the twines of the net. Reynolds number for the twines are $O(10^3)$. Drag forces on net elements are based on a time-averaged wake model, applicable for the near-field wake. Negative lift forces occurring on the downstream cylinder in a staggered arrangement is explained as interactions due to upstream generated vortices. The results are validated for 2 and 5 cylinder arrangements and a net.

1 Introduction

The resources of wild fish are limited. The recent trend is stagnating amount of wild catch. The selectivity of fishing gear has therefore become important. The research so far has mainly focused on the testing of different sorting devices. In addition, numerical models have been developed to study the shape and behavior of both trawls and purse seines. Numerical models known to the authors assume undisturbed flow. A three-dimensional net structure is a highly flexible structure where separated flow around each twine and flow-structure interaction matter. Using a structural finite element method combined with Navier-Stokes equations is impossible due to the required CPU time and data storage. Further CFD methods for this types of flow have clear physical limitations. Our objective is to develop simplified and physically justified methods. A model that describes the disturbance of the fluid flow in front of the net, due to the presence of the net by using a source distribution representing the wake flow was presented by Fredheim and Faltinsen [2]. Our focus is on cylindrical elements in the wake of each other. Drag forces are calculated using wake models combined with known drag coefficients for a single cylinder. An attempt is made to understand why cylinders in a staggered arrangement can experience mean lift force.

2 Drag on Multiple Cylinders

In a net structure at low angles of incident flow, the different twines of a net will be situated downstream of each other. I.e. we have to consider the velocity deficit generated by the different twines. This can be used as basis for calculating the mean drag force. One possible model for calculating the velocity deficit behind one cylinder is the "far wake mean velocity deficit" model presented by Schlichting [8]. Schlichting's formula agrees well with experiments in the far-field wake, but gives too large velocity deficits and a too narrow wake region in the near-field wake. To be able to get good results in the near-field wake, which is our range of interest, different modifications of the original formulation have been tried out.

Blevins [1] introduced a virtual origin of the wake. Further the constants in Schlichting's formula were modified. The time-averaged velocity deficit u_1 in a turbulent wake behind a single cylinder is, according to Blevins

$$\frac{u_1}{U_\infty} = 1.02\sqrt{\frac{DC_D}{6D+x}} \exp\left(\frac{-y^2}{0.0767DC_D\,(6D+x)}\right) \quad (1)$$

Here U_∞ is the undisturbed uniform flow in the positive x-direction, C_D and D is the drag coefficient and the diameter. The cylinder axis corresponds to $x = 0$ and $y = 0$. Blevins [1] presents a constant of 1.2 instead of 1.02 as used in equation (1). However using conservation of fluid momentum and expressing the drag force in terms of C_D and u_1, shows that this must be a misprint.

Løland [4] derived analytically the wake behind a cylinder, by including the finite dimen-

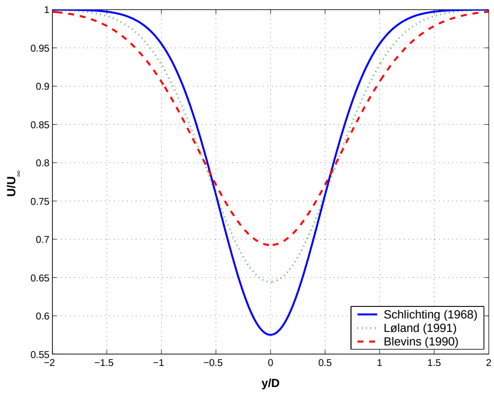

Figure 1: Velocity downstream of a single cylinder calculated using different velocity deficit models. x/D = 5.

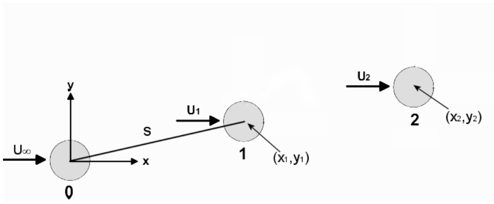

Figure 2: Illustration of several cylinders in a wake flow. s is the distance between two cylinder axis.

sion of the cylinder. His formula is

$$\frac{u_1}{U_\infty} = \frac{C_D}{4}\left(\Phi(\frac{D/2+y}{\sqrt{0.0888 C_D D x}})+ \Phi(\frac{D/2-y}{\sqrt{0.0888 C_D D x}})\right) \quad (2)$$

where Φ is the error function.

Figure 1 presents the results from the different models for x/D of 5. Compared to the original model by Schlichting, the other models have smaller velocity deficits and wider wakes. Blevins' model gives the least reduction in the velocity and the widest wake. Løland's model has the same tendency, but the magnitude of the "correction" both with respect to velocity deficit and the width of the wake are less. After approximately $20D$ there is very little difference between the models.

There are uncertainties related to how several cylinders interact and generate a total wake field (Zdravkovich [9]). A cylinder downstream will experience a wake field which is a result of the generated wake of all the preceding cylinders. We have added the velocity deficits linearly. This gives by Blevins model the following expression for the inflow velocity behind cylinder N due to the N preceding cylinders (includ-

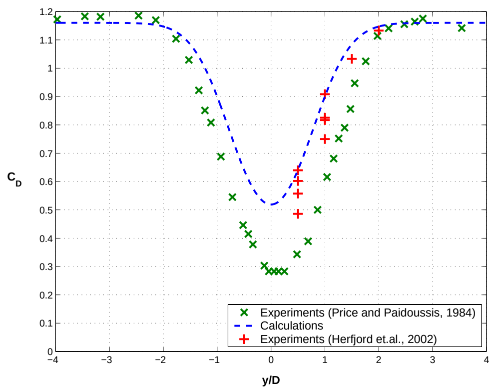

Figure 3: Drag coefficient for a cylinder in the wake of another cylinder at a distance $x/D = 5$. $Re = 2 - 0 - 6^4$.

ing cylinder 0)

$$U_N = U_\infty - \sum_{i=0}^{N-1}\left(U_i 1.02\sqrt{\frac{DC_D}{(x_N - x_i + 6D)}} \exp(\frac{-(y_N-y_i)^2}{0.0767 DC_D(x_N - x_i + 6D)})\right) \quad (3)$$

Notations refer to Figure 2. U_N is then combined with C_D for a single cylinder to find the drag force, which is non-dimensionalized with $0.5\rho D U_\infty^2$ to find the drag coefficient for a cylinder no N. ρ means mass density of the fluid.

Two cylinders In Figure 3 the drag coefficient on the downstream cylinder in a staggered arrangement at $x/D = 5$ is presented using Blevins model. Measurements by Price and Paidoussis [7] at Reynolds number, $Re = 5.3 \times 10^4$ and by Herfjord et.al. [3] at $Re = 2.0 - 6.0 \times 10^4$ are presented. D has been used as a characteristic length in Re. The calculations correspond to $Re = 1.75 \times 10^4$. The calculated results are not sensitive to Re. Herfjord et.al. presented also CFD results for $y/D = 0.5$ and $y/D = 1.0$ based on solving 2D unsteady laminar Navier-Stokes equation with FEM at $Re = 200$. Even if they assume laminar flow and we use a turbulent wake model,their results agree well with our results.

We note a relative large variation in the measured C_D-values in a rather limited Re-range where the flow on the upstream cylinder is in the subcritical flow regime with laminar boundary layer. We believe this variation is due to the turbulence in the incoming flow on the downstream cylinder, generated by the upstream cylinder. This effect the boundary layer flow and the separation points of the downstream cylinder and

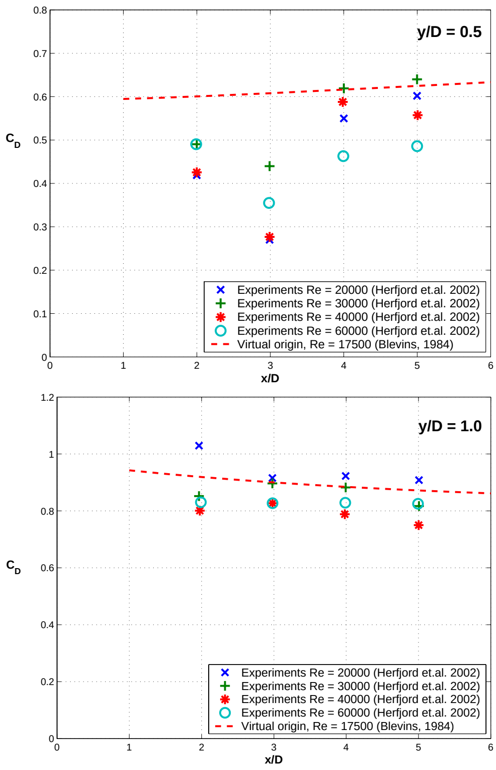

Figure 4: Drag coefficient for a cylinder in the wake of another cylinder.

then reduce the drag coefficient. Figure 14.18 in Zdravkovich [10] shows that the turbulence intensity of the incident flow can decrease C_D as much as 50% for a Reynolds number as low as 2.0×10^4. Clearly, using a time averaged velocity deficit model, we are not able to show this dependency. However our results are otherwise quite consistent with Herfjord et.al.'s experiments. In order to assess for how small x/D-values that our model applies Figure 4 shows comparisons with Herfjord et.al.'s measurements for $y/D = 0.5$ and 1 as a function of x/D. Our method gives reasonable predictions for x/D as low as 4.0 for $y/D = 0.5$ and even lower for $y/D = 1.0$. The results for $y/D = 0.5$ are consistent with tandem cylinders where abrupt changes in C_D occur at $x/D = 3.8$ (Okajima [6])

Five cylinders To further investigate the near field velocity deficit (and to get a connection to the actual net structures which consists of a great number of "cylinders"), five rigid equidistant aluminum cylinders in a row, was towed at different angles α, velocities and spacings between the cylinders. $\alpha = 0°$ corresponds to that the cylinder row is inline with the ambi-

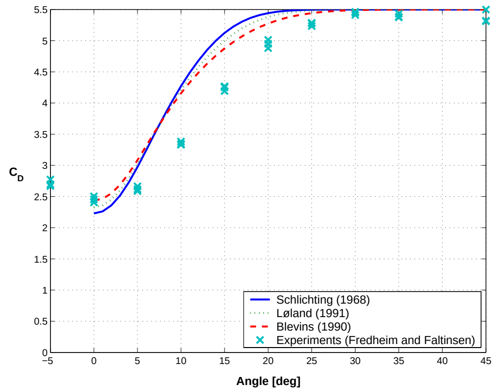

Figure 5: Drag on five cylinders in a row as a function of angle α. $s = 5D$.

ent flow. The total in-line and perpendicular force on the grid were measured. The cylinders had a diameter $D = 4.0$ [cm] and were towed with a draught $h = 0.8$ [m] and a speed of 0.5 [m/s] in the presented results This corresponds to $Re = 1.75 \times 10^4$. The drag coefficient C_D is obtained by dividing the drag force with $1/2\rho D h U_\infty^2$.

Figure 5 presents results when the distance s between the axis of two cylinders near by each other is $5D$. Figure 5 shows good agreement in general, but there are some discrepancies between the experiments and the mean velocity deficit models. At $\alpha = 0°$ the calculated drag force are too low and becomes too high with increasing α. Løland's and Blevins' models agree slightly better with the experiments than Schlichting's model. It is apparent that the models overestimate the velocity reduction for small α and give too low drag force, and at the same time the width of the wake is calculated to be too narrow. The influence of turbulence intensity in the incident flow on the downstream cylinders is believed unimportant in this case.

Figure 6 visualizes the wake behind a cylinder towed at constant speed. There is a cross flow around the cylinder bottom, such that the velocity is respectively downwards and upwards at the upstream and downstream side of the cylinder. This narrows the vertical height of the wake. There is a further contraction of the vertical extension of the wake of the wake with increasing distance downstream. The consequence for a downstream cylinder is that the lower part of the cylinder see an undisturbed incident flow. This causes a higher drag on a downstream cylinder relative to using our wake model over the whole height of the downstream

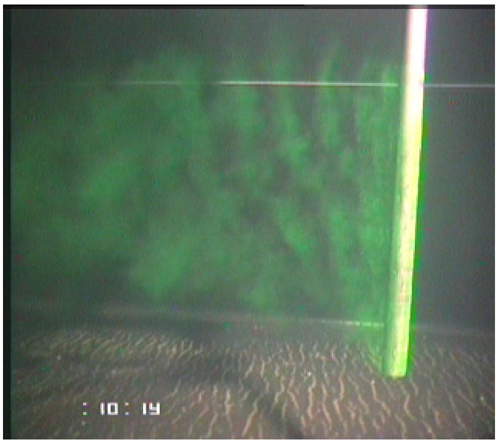

Figure 6: Visualization of three dimensional flow behind a single cylinder, towed at constant speed.

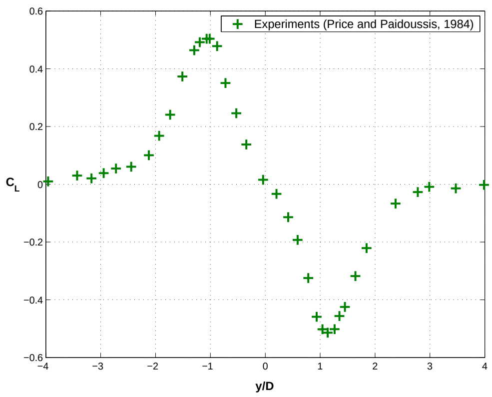

Figure 7: Mean lift coefficient for a cylinder in the wake of another cylinder. $x/D = 5$. $Re = 5.3 \times 10^4$.

cylinder. This may give the order of 10 % influence on the calculated results in Figure 5.

3 Lift on Multiple Cylinders

The experiments by Price and Paidoussis [7] (Figure 7) show a large y-component (lift) of the mean force for a certain range of y/D. The lift direction is towards the wake axis. We can not explain this negative lift force by the shear flow associated with the mean wake flow. When a pipe is in a boundary layer flow near the sea bottom, the pipe sees a similar shear flow as the downstream cylinder experiences. The pipe experiences a positive lift force.

This means we have to study the dynamics of the wake behind the upstream cylinder. The unsteadiness due to turbulence can effect the separation points of the downstream cylinder in a certain Reynolds range as earlier described.

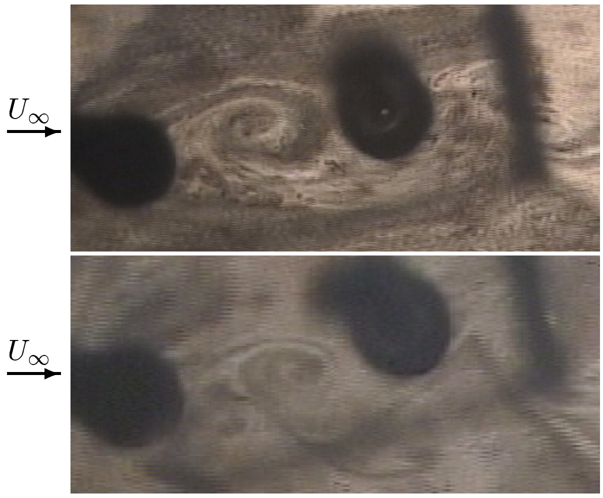

Figure 8: Visualization of the flow around and between two cylinders in a staggered arrangement. Top picture $y/D = 0.625$, bottom picture $y/D = 1.2$. $Re \sim 500$.

However we believe that the negative lift force is mainly associated with the shed large scale vortices. To support our later qualitative explanations, experimental flow visualization (see Figure 8) was carried out. The tests show two distinct occurrences. First the vortex shed from the upstream cylinder on the same side as the downstream cylinder is placed, always goes on the side towards the wake axis ("inside") of the downstream cylinder even for small y/D. Secondly the vortex shed on "outside" of the downstream cylinder is smaller than the vortex shed on the "inside". The positions of the separation points are also affected.

We will try to explain the negative lift force in terms of the shed vortices from the upstream cylinder. We assume the center of the downstream cylinder has a positive y/D-value such that the vortex shed from the upper side of the upstream cylinder is incident to the downstream cylinder. We simplify the flow around the downstream cylinder to first consist of three parts. Part 1 is the incident vortex with an image vortex inside the cylinder in order to satisfy the body boundary conditions (Milne-Thomson [5]). The vortex strength can be approximated as $2.5 U_\infty D$. Part 2 is an incident mean flow associated with the mean wake flow of the upstream cylinder, evaluated at the downstream cylinder origo. Part 3 is a source in the center of the downstream cylinder to represent its own wake. The source strength is by Lagally's theorem equal to $C_D U D$ where U is the incident

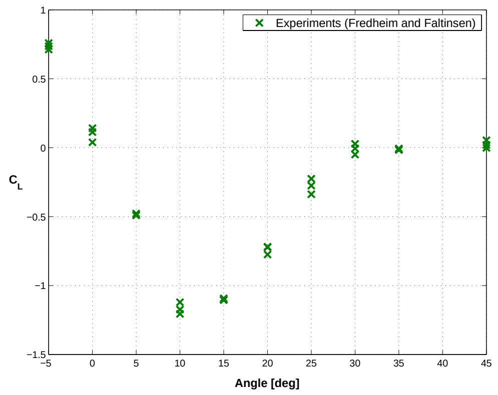

Figure 9: Mean lift on five cylinders in a row as a function of angle α. Same conditions as in Figure 5.

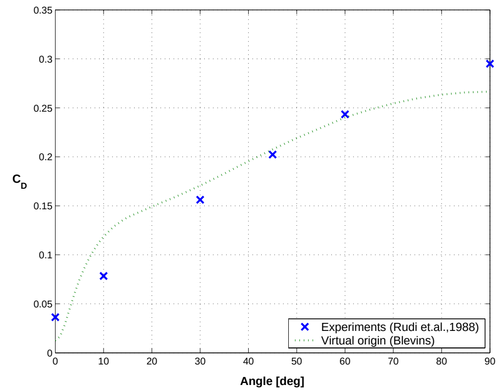

Figure 10: Drag on a plane net as a function angle α. $Sn = 0.243$.

mean flow velocity. The image vortex causes an anti-clockwise angular velocity of the vortex around the downstream cylinder. The result is that the vortex will get a path below the downstream cylinder. How close the vortex comes to the lower surface part and hence how strong it will affect the lift depends on the ambient vortex position relative to the downstream cylinder as well as the three flow components. The simplified analysis neglects the influence of the vortex shed from the lower side of the upstream cylinder and assumes implicitly that the y/D-values of the center of the downstream cylinder is not small. But a small y/D-values would cause nearly the same strength of the shed vortices on the upper and the lower side of the downstream cylinder, i.e. an oscillatory lift force with nearly zero mean value. The vertical force due to the vortex will change with time, but will in average be negative. Further this vortex causes an increased strength of the shed vortex from the lower side of the downstream cylinder. This adds to the negative lift. The total lift on the downstream cylinder will be oscillatory, but with a mean negative lift. If we had assumed a negative y/D-value for the center of the downstream cylinder, the arguments would be similar. The calculations explain qualitatively the y/D-dependence of the lift force.

Herfjord et.al [3] presented unsatisfactory numerical results for the lift force for the case presented in Figure 7. This was both based on using the commercial code Fluent as well as their own Navier-Stokes solver. Our analysis suggests that the y/D dependence of C_L for other x/D-values is related to the ambient path of shed vortices from the upstream cylinder. Blevins [1] figure 5-18 of positions of maximum absolute value of lift supports this.

Figure 9 shows our experimental results for the mean lift force on 5 cylinders as function of α. We note the similarity between the results in Figure 7 and 9, i.e. we can use the two cylinder results to explain the results for multiple cylinders.

4 Net Structures

Since the Reynolds number of a twine element of a net in a current is typically $1.0 - 5.0 \times 10^3$, the effect of turbulence intensity on the drag force on twine elements in the wake of others is not important. Further since typical distances s between nearby twine elements is in the range of $5 - 12D$, the requirement that $s > 3.8D$ for our drag model is satisfied.

Figure 10 shows a good agreement between theory and experiments for the drag on a plane net as a function of α, when the solidity ratio Sn is 0.243. Sn means the ratio between the projected area A_n of the net and the total area A enclosed by the net. C_D is obtained by nondimensionalizing the drag force with $0.5\rho A U_\infty^2$. Due to the nature of a net structure, it will not be possible during experiments to avoid some deformation of the net itself, which again will not only have an influence on inflow of the net and thereby the resulting drag force, but also on the "effective" angle α. Deformation of the net is not accounted for in our results.

Numerical calculations has also been done for a cone of 2.0 [m] length, and circular front opening with a diameter of 1.5 [m] and an end opening of 0.15 [m]. Only mean drag forces were considered. Flow structure interaction was accounted for by modeling the net structure as a FEM model and finding the mean equilibrium position of the net. The twines where modeled as cylinders with a diameter of 4.0 [cm], with 20 twines in the longitudinal direction and 18 around the circumference. This give a solidity ratio S_n from 0.3 in the front to 1.0 at the end. Calculated total drag on the cone, without any correction for the velocity deficit due to wake generation, is 1.28×10^3 [N] and with correction becomes 8.76×10^2 [N] which is a large difference.

Since the shape of a trawl is an important issue regarding fishing efficiency, and also the selectivity performance of the trawl, the investigated lift effect on cylinders in staggered arrangement becomes an important aspect when modeling a trawl. Blevins [1] pointed out that large amplitude galloping motion can occur for a cylinder in the wake of another cylinder. This is associated with both the negative mean lift as well as the effect of the wake on the drag on the downstream cylinder. The relevance of this for a net structure has to be clarified.

5 Conclusions

The complexity of the flow around a fishing net or trawl, makes CFD calculations presently impossible. Simple physically based load models are needed. Our focus is on the flow around the twine elements of the fishing net, when a twine element is in the wake of another element. Experimental results for interaction between two cylinders in staggered arrangement are used. Interesting ratios s/D between the cylinder axis distance and the cylinder diameter are in the range of 5 to 12. The near-field wake model of the mean flow by Blevins [1] can be used to calculate the drag force on a downstream cylinder when $s/D > 3.8$. The results are validated by experiments at Reynolds numbers from 2.0×10^4 to 6.0×10^4. The drag force on the downstream cylinder is then sensitive to the turbulence intensity of the incident flow. However this is a minor problem for our Reynolds numbers of practical interest, $1.0 - 5.0 \times 10^3$. The downstream cylinder can in certain staggered arrangements experience a significant mean negative lift force, acting towards the mean wake axis. This is explained by experiments and simple theory as interaction between vortices shed from the upstream cylinder and the flow around the downstream cylinder. Our experimental results for five cylinders in a row show similarities with the two cylinder results. The simple theoretical method shows good agreement with experimental results for drag forces on a plane net.

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