DRAG FORCES AND DEFORMATION OF AQUACULTURE CAGES – FULL-SCALE TOWING TESTS IN THE FIELD

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ABSTRACT

Fish cages can experience strong loads due to hydrodynamic forces in the sea. Numerical models are often used to estimate drag forces on net cages, and the development and validation of such models is mostly based on laboratory tests that can be performed under controlled conditions. However, several environmental factors are difficult to account for in a laboratory. Experiments using full-scale fish cages in the sea could produce valuable data and new insights on the fluid-structure interaction between sea-cages and ambient flows, given sufficient control over environmental factors. Today very little field data is available on the forces on full scale fish cages in the sea.

In this study, an Atlantic salmon cage (12 m diameter, 6 m depth) was towed in a fjord environment at 5 different speeds to induce a relative water current past the net between 0.1 ms^{-1} and 1 ms^{-1}. Drag on the cage was measured using a load shackle attached to the towing rope and net deformation and cage volume were calculated based on the positions of pressure tags mounted to the net cage. The towing method produced consistent results on deformation in the range from 0.2 – 1 m/s, and the volume of the net pen decreased almost linearly from 86 % (0.2 ms^{-1}) up to 33% (1.0 ms^{-1}). Measured drag forces and their relationship to flow speed were consistent with existing literature. Drag calculations for net cages generally consider flow speed reduction inside the cage due to blockage effects. However, there are large differences in the flow reduction inside net cages found in few laboratory and field studies, which calls for better descriptions of the flow past net cages. This is illustrated by the comparison of drag calculated by a simple, deterministic model, using a static flow speed reduction of 20% inside the cage and a variable flow speed reduction that depends on the ambient flow speed. The results from this study provide valuable information about the interplay of flow speed, net deformation and drag on a full scale fish cage at different flow speeds and underline the need for a better description of the flow past net cages.

1. INTRODUCTION

Global marine finfish production has almost doubled within the past decade (FAO, 2012) with a total production of about 5.5 million tons in 2012 and continued growth in the future is expected. While some fish farms are located in sheltered areas, for example inside of fjords, an increasing number of production sites is moved towards more exposed areas. Even though other cage concepts have been proposed and are in use, most marine fish farms today use gravity type net cages, which employ weights to retain the shape of a net that is connected to floaters at the water surface.

Currents cause hydrodynamic loads on cages and their moorings (Klebert, et al., 2013), which in turn attenuate and redirect the flow. Water flow in the sea is variable on small and large temporal and spacial scales and gravity cages are flexible and deform under hydrodynamic loads, which leads to complex interactions between cages and currents. A good understanding of these interactions is needed to minimize environmental effects of aquaculture and to ensure the structural safety of fish farm structures as well as good fish health and welfare. The collapse of a complete fish farm during a storm event in Norway in 2005 (Jensen, et al., 2010) highlights that strong hydrodynamic loads on cages and moorings can threaten the structural integrity. The behaviour of and drag on nets in currents and waves have been investigated in a number of studies e.g. (Aarsnes, et al., 1990; Balash, et al., 2009; Gansel, et al., 2014a; Huang, et al., 2006; Lader, et al., 2008; Le Bris, Marichal, 1998; Løland, 1991; Milne, 1972; Moe, et al., 2010; Zhan, et al., 2006) and several authors propose models describing the relationship of flow speed and the drag on nets.

The solidity and shape of nets affects flow patterns past fish cages and the water exchange across nets (e.g.(Bi, et al., 2013; Gansel, et al., 2012; Harendza, et al., 2008), thus defining the transport of dissolved and particulate material through fish cages. Good water exchange rates in fish cages are desired to maximize the oxygen inflow and waste removal. However, on a number of Norwegian salmon farms attempts are made to steer water in an upper layer around cages to prevent the inflow of pathogens across the net (e.g. (Frank, et al., 2014; Stien, et al., 2012)). In the sea, fouling can accumulate on nets at fast rates (e.g. (Bloecher, et al., 2013; Braithwaite, et al., 2007; Yamamoto, et al., 1988), thereby occluding net apertures, which restricts water exchange across nets and increases net drag. Increased drag causes stronger deformation, which may lead to contact between nets and chains holding the sinker tubes of large circular fish cages. This can ultimately cause damages of the net due to chafing. (Jensen, et al., 2010) report structural failure, specifically holes in nets, to be the major cause for escapes from salmon cages in Norway within a three year period from late

2006 on. Strongly deformed nets lead to a significant change of the shape and volume of fish cages and can increase the effective stocking density (e.g. (Lader, et al., 2008; Moe, et al., 2010).

Laboratory studies allow controlled investigations of the effect of single or defined sets of parameters (e.g. (Lader, Enerhaug, 2005; Løland, 1991; Zhao, et al., 2015). Therefore they are well suited to develop and validate models, but such tests are size restricted and findings under laboratory conditions are not always directly transferable to more complex situations in the sea. Field studies assure realistic conditions and can include fish (e.g. (DeCew, et al., 2013; Gansel, et al., 2014b; Johansson, et al., 2014; Lader, et al., 2008)), but environmental factors often cannot be systematically varied or even influenced, and it may be difficult to monitor relevant parameters for a given study. Thus, it can prove challenging to investigate single factors. Experiments combining the strengths of laboratory and field experiments, while limiting the restrictions are highly desirable.

Scale models of net cages can be moved in towing tanks, in order to determine deformation and forces on the system from varying current speeds. This study aims to investigate whether the towing technique can be successfully employed using full-scale fish cages in the sea. Secondary aims of the study are investigations of i) the behaviour of a full scale cage in currents and ii) how the interaction of water flow and flexible net cages affects drag.

2. MATERIALS AND METHODS

A polar circle fish cage with a diameter of 12 m was towed at five different speeds between 0.2 ms^{-1} and 1 ms^{-1} in a fjord environment of southern Norway, in Masfjorden, between Eikemofoss and Solheim. The area and the tow-paths are shown in Fig. 1.

Figure 1

2.1 SETUP

The cage collar consisted of two circular polyethylene rings (Polar circle, 12 meter diameter) mounted on top of a square steel cage floater arrangement to avoid deformations. The net (Egersund net AS, 15 mm half mesh width, Nr. 20) had a flat bottom, and it was mounted so that the bottom line was at 6 m depth in slack water. Eight concrete weights (35 kg in water, each), in addition to a leaded bottom rope (0.5 kg per meter) were used to weigh down the net to reduce deformation. The weights were attached to the floating collar and submerged to 7 m depth on the outside of the net with even horizontal spacing, where they were connected to the bottom rope of the net (Fig. 2). A steel platform extending to the upstream side acted as mount for the towing rope and a current profiler (NORTEK Aquadopp 600MHz) one diameter upstream from the net (Figs. 2 and 3). All data presented in this paper are on the net only, and Table 1 summarizes relevant specifications of the net and weight system.

The cage was towed with a two-hull, water jet powered workboat (Salma, 15 m, 0.7 m keel depth). A force shackle (Strainstall, type 4991) was mounted at the boat end of a 350 m tow rope as shown in Fig. 3. Depth recording tags (DST centi-TD) were mounted directly to the net at 12 locations as shown in Fig. 2 to monitor the net deformation. A mobile network corrected GPS system (Septentrio PolaRx2e@ L1/L2 GPS RTK-receiver with PolaNt L1/L2 geodetic GPS-antenna) was used to measure boat speed and to record towpaths.

Figure 2

Table 1

2.2 TESTS AND DATA ANALYSIS

The tows were conducted on straight transects, with the aim to achieve stable GPS speeds of 0.2, 0.3, 0.5, 0,7 and 1.0 m/s. These speeds are the nominal flow speeds of this study. Each towing test lasted for 10 minutes, and was started when alignment of the boat and the towing assembly was satisfactory (that is, when the towing rope was straight, such as pictured in Fig. 3). Constant micro-adjustments by the captain were necessary to assure straight tow-paths. The cage was first towed at the five nominal speeds without the net submerged, and then at similar speeds with the net submerged. For all of these 10 tests time averages were calculated of:

- the flow speed one diameter upstream from the cage,
- the drag force on the towed assembly
- positions of the depth sensors.

Fig. 1 and Table 2 give an overview of transects, time intervals and nominal tow speeds together with measurement results.

The length of the tow rope, positions of transects and timing of individual tests were chosen to minimize the possibility for interaction of the boat wake with the test setup and the effect of such interactions, while still maintaining control over the cage system. Only for the two test with the fastest relative flow speeds did the tow length exceed the length of the tow rope (350 m). At the fastest tests the wake behind the boat had over 5 minutes to develop, and due to the circulation in the fjord the net cage would only hit the wake off center. During towing tests without net, the concrete weights were taken off cage system and onto the tow-boat, while the net was left on the floaters. This was done to achieve a similar floatation depth of the floaters during tests without and with the net and weights submerged.

The average flow speed in 10 equally thick depth layers 1.4 - 11.4 m (1 m thickness per layer) below the surface was recorded by the Aquadopp profiler at one diameter upstream from the cage at a frequency of 1 Hz. Depth profiles of the velocity are shown in Fig. 6. The flow velocity was averaged over 10 minutes as specified in Table 2 for each test interval and per depth layer. The net deformed differently at different tow speeds and therefore only depth layers of the flow velocity down to the depth of the net were used to calculate an average flow upstream from the cage. In other words, the average flow velocity was calculated as a time average over the depth of the cage's net for each test. The flow speed in the uppermost layer from 1.4 to 2.4 m depth was used for an estimate of the surface flow upstream from the floaters in tests without the net.

Figure 3

The factory calibration of the load shackle was used to calculate all forces in Newton. All force measurements were carried out at a frequency of 100 Hz and logged at 1 Hz, resulting in 60.000 measurements and 600 logged time averages per time interval as specified in Table 2. The average force and standard deviation were calculated for each of the time intervals. Two series of towing tests were conducted at five pre-determined tow speeds. One series without and one series with net and weights attached to the floaters, the difference between the two series allowed the calculation of the drag force on only the net.

2.2.1 CALCULATION OF CAGE DEFORMATION

Depth recording DST centi-TD tags were positioned on the cage in two depth layers as described above and shown in Fig. 2. These tags only measure depth, and therefore their exact three dimensional location needs to be approximated. First, it is assumed that the tags move in only one plane; with the current and upwards to the surface. Second, four extra nodes are introduced in the grid spanned by the tags to obtain an octagon, as shown by the green dots in Fig. 5. The net was fixed to a circular ring that was attached to a fixed steel platform (see Fig. 2), which means that the net was fixed in position at the surface with no possibility for the net to deform at the attachments points at the surface. Therefore, 8 virtual additional nodes were introduced on the surface with fixed position (Fig. 5, violet spheres),

The calculations of the positions of tags were conducted as follows (see Fig. 4 for reference). Without current, when the net is un-deformed, nodes 0, A and B are in depths h_0, h_a and h_b, respectively. All nodes are at x-position x_0. When the net deforms, nodes A and B will change their positions accordingly. The depth tags measure the new depth positions of nodes A and B to be $h_{a'}$ and $h_{b'}$. Node 0 remains unchanged in depth, as it is associated with the attachment of the net to a rigid steel frame at the surface. The new horizontal positions $x_{a'}$ and $x_{b'}$ of nodes A and B are found by geometric triangulation from the depth displacement of the nodes.

The position of the green nodes in Fig. 5 were calculated using the average of the displacement of the two neighboring nodes in the same layer.

Figure 4

The positions of the tags define a convex polyhedron of which the volume can be calculated with different methods. In this study, the cage volume was calculated by separating the cage into several simpler polyhedrons, each defined by the nodes in two neighboring depth layers, and then calculating the sum of their volumes as the total cage volume. This method is described in detail in (Klebert, et al., 2015).

2.2.2 CALCULATION OF THE ANGLE BETWEEN TRIANGULAR NET ELEMENTS AND FLOW DIRECTION

In order to find a measure on the orientation of the net planes, the net was divided into triangles spanned by the measuring points as shown in Fig. 5. Then the shape of the net is simplified by assuming that the net surface is flat within the triangles. The orientation of the net planes, which is needed for the drag force calculation, is defined by the angle between the normal vectors of the planes and the flow direction.

2.2.3 CALCULATION OF DRAG FORCES

In this section, we describe two different methods for modelling drag forces on the net, considering different flow speed reduction inside net cages. These are later compared to field measurements. The methods differ by the amount of flow reduction inside fish cages (method I based on laboratory tests and method II based on larger scale filed tests), and they are based on deterministic model by (Aarsnes, et al., 1990) and (Kristiansen, Faltinsen, 2012) describing the relationship between net solidity, Reynolds number, drag coefficient and flow velocity (speed and angle between flow and net). The reasoning of using these relatively simple calculations, rather than to use more complex models, is to show the effect of a flow speed reduction inside fish cages on drag and the importance of proper knowledge of the flow inside net cages when evaluating hydrodynamic forces. The importance of the blockage effect of nets and the resulting flow reduction inside cages may seem obvious, but the flow inside full-scale fish cages is complex and dynamic in time and space, and it is, to date, not well understood. The calculations and the reasoning behind those is explained in more detail in sections Method I and Method II.

A number of studies investigated the drag on nylon net panels (e.g. (Aarsnes, et al., 1990; Balash, et al., 2009; Løland, 1991; Milne, 1972; Zhan, et al., 2006)). Some of these studied the effects of net solidity and angle between the incoming flow and the net plane and suggested empirically derived formulae for the calculation of drag coefficients on straight net panels in a uniform flow. Equation (1) is an example of such a formulation for the calculation of drag coefficient (C_D) of plane nylon nets proposed by (Aarsnes, et al., 1990):

$$C_D = 0.04 + (-0.04 + Sn - 1.24\, Sn^2 + 13.7\, Sn^3) \cos(\theta) \tag{1}$$

with Sn is the net solidity and Θ is the angle between the flow direction and the net plane. The solidity of the net used in the present study ($Sn = 0.27$) falls within the solidity range, for which this formulation is valid. It should be noted that eq. (1) is based on tests with knotted nets, while the present study used a Raschel-type net.
Later studies introduced more elaborate methods for the calculation of drag on cylindrical net structures (e.g. (Balash, et al., 2009; Kristiansen, Faltinsen, 2012)), and we include a drag calculation based on (Kristiansen, Faltinsen, 2012) for comparison with the simpler calculation methods based on (Aarsnes, et al., 1990) and our experimental results. For this purpose we also used C_D as proposed by (Kristiansen, Faltinsen, 2012) for drag calculations:

$$C_D = C_d(a_1 cos\theta + a_3 cos3\theta) \tag{2}$$

with $a_1 = 0.9$ and $a_3 = 0.1$ and C_d is:

$$C_d = C_N(\theta), for\ \theta = 0 \tag{3}$$

with the normal force coefficient C_N is:

$$C_N(\theta) = \frac{C_D^{circ.cyl} Sn(2-Sn)}{2(1-Sn)^2} cos^2\theta \tag{4}$$

and the circular cylinder C_D is:

$$\begin{aligned} C_D^{circ.cyl} = &-78.46675 + 254.73873(log_{10}Re) - 327.8864(log_{10}Re)^2 + 223.64577(log_{10}Re)^3 - 87.92234(log_{10}Re)^4 \\ &+20.00769(log_{10}Re)^5 - 2.44894(log_{10}Re)^6 + 0.12479(log_{10}Re)^7 \end{aligned} \tag{5}$$

The dependency of C_D based on eq. (2) was then expressed by using θ as calculated for each individual triangular net panel described in section 2.2.2.

The drag on a net panel in a uniform flow depends on the density of the fluid (ρ), the flow speed (u), the area of the net (A) and its drag coefficient (C_D):

$$F_D = \tfrac{1}{2} \rho\, u^2\, C_D\, A \tag{6}$$

The drag on a fish cage can therefore be calculated from eq. (6) when all four parameters are known. The area of a fish cage (from diameter and depth of the cage), the density of seawater (with conductivity/temperature/density sensors) and the flow speed (with flow meters or profilers) can be measured. Calculating the drag coefficient for a flexible fish net in currents is not trivial, as the net deforms in the flow and changes its shape. That means that one of the factors in eq. (6) is not easily determined. However, any given net structure may be approximated by a number of flat net panels. The forces on each flat net panel can then be calculated and the total force on the complete net structure can be expressed as the sum of all individual net panels.

The following describes two methods this study used to estimate forces on the fish cage based on measurements and assumptions of net deformation and flow attenuation. For each of the two methods calculations were made using both formulations for C_D shown in eqs. (1) and (2). It should be noted that these methods are not meant to model the cage drag to include all important physical processes of the fluid-net interaction. However, the differences between methods I and II, which are based on deterministic models, taking into account a variety of important factors and processes for the flow past nets and the resulting drag, will show how important good knowledge of the flow past net cages is for proper drag force estimation.

Method I: The deformation of the fish cage was estimated through the use of pressure sensors as described in section *Setup* and in Figs. 2 and 5, and the position of the vertical part of the net was defined at 24 distinct locations at all times. 32 flat, triangular net panels and their orientation in three dimensions were calculated between these locations, as shown in Fig. 5. A number of studies investigating the flow speed inside small cages in the laboratory and in the field found flow speed reduction inside the cages of about

10 – 20 % of the upstream flow speed (e.g. (Fredriksson, et al., 2007; Gansel, et al., 2012; Inoue, 1972; Løland, 1991; Zhao, et al., 2015)). Some of these studies did not specify the net solidity, but the solidity of the net used by some of these authors was relatively close to that of the net used in this study (e.g. (Løland, 1991): Sn = 0.24; present study: Sn = 0.27). Method I of the present study therefore assumes a flow speed reduction inside the cage as follows: the measured upstream flow speed was assumed for the drag calculations on net panels in the upstream half, while a 20 % reduced velocity was assumed for the 16 triangular net panels in the downstream half of the cage (see Fig. 2a). The drag on the net cage was then calculated as the sum of all triangular net panels. This is the simplest method for the estimation of cage drag in the present study, and is in the following called method I.

Method II: Not all studies show a flow speed reduction as assumed for method I. For example, a recent field study on a stocked, commercial farm site shows varying flow reduction from almost 0% to about 50% (Johansson, et al., 2014). The total flow reduction generally was low at the lowest flow speeds around 0.1 ms^{-1}, while it was about 50% at upstream flow speeds of 0.3 – 0.7 ms^{-1}. The authors of the present study conducted several sets of experiments with the exact same cage setup as used in this study and measured the flow speed upstream, downstream and inside the cage. During those tests, the flow speed inside the cage was strongly dependent on the upstream flow speed, with stronger flow attenuation in faster currents. The preliminary results from these tests generally agree with the findings of (Johansson, et al., 2014), but flow reduction inside the cage was more pronounced at high upstream flow speeds. Accordingly, method II of this study uses flow reductions as found in experiments with this exact cage setup, namely 50 %, 70 %, 70 % and 70 % reduction of the upstream flow speed at flow speeds of 0.156 ms^{-1}, 0.312 ms^{-1}, 0.509 ms^{-1}, 0.732 ms^{-1} and 1.056 ms^{-1}, respectively (unpublished data).

Figure 5

3. RESULTS

Nominal speeds and measured flow speeds upstream from the cage are shown in Table 2. The measured flow speeds matched the intended nominal flow speeds well with a difference of < 6 cm/s for any given test. The towing directions measured on the tow boat during the tests were mostly between 70 and 80 degrees (heading between east-northeast and east, see Fig. 1). In still water, the measured flow direction upstream from the cage would be opposite to the tow direction in still water. That means without ambient circulation in the fjord flow directions of 250 to 260 degrees were expected. Measured directions were between 240 and 280 degrees with deviations from the expected directions within the range of 5 degrees for most tests. Higher deviations of 20 – 25 degrees occurred only for tests with net and weights submerged at nominal tow speeds of 0.2 and 0.3 ms^{-1}. Only the flow speed opposed to the tow direction should be considered for the calculation of in-line drag forces on the net, as it is only this component of the flow that contributes to drag along an axis defined by the tow direction. The difference between the measured flow velocity and its component opposite to the towing direction is about 10 % for the largest deviations between expected and measured direction (20 – 25 degrees at low tow speeds with the net submerged) and << 5 % for all other tests.

The standard deviation of flow speed ranged from about 30 % of the mean velocity at low speeds and tests with only floaters to under 10 % for almost all test with the net submerged (Table 2). The standard deviation of the flow speed in percent of the mean speed during single tests generally decreased with increasing tow speed, while the total standard deviation was relatively stable (tests with only floaters) or increased with varying flow velocity (tests with net submerged). The tow direction during the slowest test with only floaters was unstable and therefore the results from this test were not used.

Fig. 6 shows depth profiles of the flow speed relative to the cage system during all tests. There was generally little variation of the flow speed with depth. Especially during tests with the net submerged, the flow velocities were rather even over the depth of the cage. The flow direction (not shown) was stable with depth during all tests.

Table 2

Figure 6

Fig. 7 and table 2 show the deformation of the fish cage at the five flow speeds, based on the estimated positions of the pressure sensors. Net deformation increased with flow speed (Fig. 7) and the deformation was more pronounced on the front half of the cage than on the back half. Cage deformation is connected to lifting of the net and, accordingly, the average depth of the fish cage decreased with increasing flow speed. The decrease in depth is almost linear at flow speeds between roughly 0.15 and 0.7 m^{-s}, and it is relatively slower at very slow (< 0.15 m^{-s}) and high (> 0.7 m^{-s}) flow speeds. The volume reduction of the net followed the same trend as the cage depth and these two measures were proportional almost throughout the entire flow speed range of the present tests (0.15 m^{-s} to 1 m^{-s}). The drag force on the net increased with increased flow speed (Fig. 8). The rate at which the drag increased was lower at higher flow velocities. While the drag increased by roughly 1.4 kN with a velocity increase from 0.3 m^{-s} to 0.5 m^{-s}, the increase was approximately 0.85 kN and 0.3 kN for a velocity increase from 0.5 m^{-s} to 0.7 m^{-s} and 0.7 m^{-s} to 1 m^{-s}, respectively.

Figure 8

Figure 9

Fig. 9 compares the measured and calculated drag on the fish cage. Measured drag was only available for flow speeds from 0.3 ms^{-1} to 1 ms^{-1}, while the drag was calculated with methods I and II as described in table 3 for speeds < 0.2 ms^{-1} to >1 ms^{-1}. Exact values of the drag are shown in table 3, where measurement results of the drag on the net are shown in kN and the calculated drag is shown in kN (upper panel) and in percent of the measured drag (lower panel). The measured drag on the net cage generally increased with increasing flow speed. The measured drag increased relatively slower at higher speeds and a curve drawn through markers for measured drag in Fig. 9 (black crosses) flattens at high speeds. This is in contrast to the calculated drag based on both calculation methods, for which the rate of drag increase increases with the flow speed. A second order polynomial fit described the relationship between flow speed and measured drag force well ($R^2 > 0.99$) for calculations based on (Aarsnes, et al., 1990) (Eq. 1), while calculations based on (Kristiansen, Faltinsen, 2012) are well described with a third order polynomial ($R^2 > 0.99$). The calculated drag based on **method I**, taking into account the deformation of the net (deformation from actual field measurements during the towing tests, which is translates into changes in the angle of attack in eq. (1) for drag calculations) and a flow speed reduction of 20 %, distinctly overestimates drag at all flow speeds. The difference between these calculations and measured drag increases with increasing flow speed (Fig. 9; blue diamonds). The calculation of C_D based on (Kristiansen, Faltinsen, 2012) leads to lower drag at all flow speeds and the discrepancy between drag estimated based on (Kristiansen, Faltinsen, 2012) and (Aarsnes, et al., 1990) increases with flow speed. Already at an upstream flow speed of 0.3 ms^{-1} the drag is overestimated with over 40 % ((Aarsnes, et al., 1990)) and almost 30 % (Kristiansen, Faltinsen, 2012). At the highest flow speed of about 1 ms^{-1}, the method I overestimates drag with almost 500 % (Aarsnes, et al., 1990) and over 300 % (Kristiansen, Faltinsen, 2012).

Introducing a flow speed dependent flow reduction (**method II**, Fig. 9, green triangles) results in a much better fit with measurements at low flow speed and estimated drag deviate with less than 10 % from the measured drag at 0.3 ms^{-1}. While drag based on eqs. (1) (Aarsnes, et al., 1990) is overestimated, drag is underestimated by method II based on eq. (2) (Kristiansen, Faltinsen, 2012). Over and underestimation increase to about 20 % at a flow speed of 0.5 ms^{-1}. At 0.73 ms^{-1} flow speed method II based on (Kristiansen, Faltinsen, 2012) is similar to the measured drag, while the calculation based on (Aarsnes, et al., 1990) overestimated drag with about 60 %. At the highest flow speed both calculations overestimate drag substantially.

Table 3

4. DISCUSSION

4.1 TOWING AS METHOD

The tow-direction of the tow-boat was kept stable for long time periods during all test (Fig. 1) with the tow rope tensioned and straight (for example see Fig. 3). The flow speed measured upstream from the fish cage was reasonably stable during almost all tests (except for the slowest tow speed without the net submerged) and did not vary much with depth (Fig. 6). The time averaged flow speeds were close to the nominal tow speeds with standard deviations within the range of a reference case for which the cage was freely drifting (see table 2). The speed of the boat was kept at nominal tow speeds based on GPS measurements. Good fits between the nominal tow speed and the measured flow speed at the cage suggests little ambient flow in or opposite to the tow-direction. In still water the flow direction measured by the velocity profiler should be opposite to the tow-direction. Ambient flow at angles to the tow direction would alter the flow measured the current profiler, as a combination of ambient flow and induced flow by the towing would be measured. Ambient flow could also lead to different drift of the tow-boat and the cage, which could cause a sideways drift of the cage in comparison to the tow-path of the boat. During all tests the tow-direction and measured flow direction were close to opposite, suggesting little influence of any ambient flow at angles to the tow-direction.

All of the above suggests that towing allows controlling the flow past a fish cage (or other structures), given suitable environmental conditions. Marine and freshwater environments with little ambient flow or uniform flow parallel to the tow-direction with little depth variation may be a prerequisite for good results of such tests. There were no waves above a height of few centimeters during the tests and waves may lead to additional challenges as the tension on the tow rope will vary due to larger independent variations of the movement of the boat and cage, thus leading to temporal variations of the rope tension.

Towing tests in the field allow the use of large fish cages, potentially up to the largest sizes commercially used today, thereby opening a possibility to investigate stocked fish cages. Not only can different net cages be tested in different current conditions, but also can the effects of fish on net cages be investigated. Additionally, tow tests may help to investigate and understand fish behavior under systematically varied flow conditions.

4.2 FORCE MEASUREMENTS

The setup of the tests was reasonably simple with the cage and the tow-boat being connected by a long rope in a fjord environment without (noteworthy) waves. The tests were conducted in the field and a number of factors may have contributed to variations and errors in the force measurements. For example, the flow, though reasonably stable, was not completely uniform in space and time, which means that the hydrodynamic loading on the cage may not have been perfectly aligned with the tow-direction at all times. Also the tow-rope could slightly stretch and may have acted as a very stiff spring, causing fluctuations at the load shackle. However, all forces are calculated as time averages over a period of 10 minutes, and effects of small temporal fluctuations of the forces on the load shackle due to flexibility in the rope and factors like non-uniform flow and turbulence are supposedly small. As discussed in the previous section, there was little depth variation of the ambient flow, the ambient flow was rather weak in comparison to the flow past the cage induced by towing and there was little influence from cross-flow in comparison to the tow-direction. The standard deviation within the time series' of force measurements was between 3 % and 22 % of the average force for tests without the net and within the range of 1 % to 2 % with the net submerged. This suggests reliable force measurements during all tests, which is underlined by the relationships between flow speed and drag force: linear and polynomial fits to the relationships between these parameters for tests without and with net were very good with $R^2 = 0.998$ (only floaters, 2nd order polynomial fit) and $R^2 = 0.992$ (floaters and net, linear fit). More scatter would be expected for less reliable measurements with a larger inherent error. The polynomial fit reveals an exponential increase of the drag on the floaters with increasing flow speed, which is expected for rigid bodies in a uniform flow. The linear relationship between drag and flow speed when the net was submerged from the floaters may indicate that the net deformation partly balances the force increase with the flow speed. This will be discussed in more detail in the following sections.

The above discussion of the physical environment during the tow-tests and the force measurements leads to the assumption that towing tests allow stable and reliable drag measurements on fish cages, given favorable ambient flow conditions (low flow speed, uniform depth profile and little horizontal variation) and stable tow-velocities.

4.3 DEFORMATION AND DRAG FORCES

4.3.1 MEASUREMENTS

The hydrodynamic forces on the net cage increased with increasing flow speed, leading to lift of the bottom closer to the surface. The bottom rope was lifted by almost 2/3 of the initial net depth in still water to a depth of about 2 m (Figs. 7 and 8). We assumed a deformation of the net only in the current direction and the upward lift of the net was proportional to the volume reduction of the cage. The rate of net deformation and associated volume decrease seems to be slightly reduced at the low and high end of the flow speeds tested in this study. This pattern is not very pronounced, but, as a trend, fits to laboratory experiments and numerical results of other studies (e.g. (Huang, et al., 2006; Lader, Enerhaug, 2005; Moe, et al., 2010). Field measurements by (Lader, et al., 2008), using square and triangular net cages, did not show this relationship. However, in their study flow velocity was highly variable and there was substantial scatter in the relationship between current velocity and relative area and cage volume. Together with the difference in cage shape, this might explain differences between the present study and (Lader, et al., 2008).

Drag increased with increasing flow speed (Figs. 8 and 9), but the rate of drag increase became lower with flow speed. This was especially evident at the highest speed, at which the net deformation was largest. This trend corresponds well with the findings of other authors (Huang, et al., 2006; Lader, Enerhaug, 2005; Moe, et al., 2010). (Lader, Enerhaug, 2005) performed laboratory measurements of the deformation of scale models of fish cages with different amounts of weights to the bottom of the net. They found the rate of volume reduction to increase with increasing flow speed at low speeds. For the test with the lowest amount of weights (Lader, Enerhaug, 2005) used, they found a critical flow speed at which the relationship between flow speed and deformation had an inflection point followed by a decrease in the deformation rate of the cage with further increase of the flow speed. They suggest that inflection points also have to exist at some critical flow velocity for the test with heavier weights attached to the net, but that this critical speed was outside of the range of their tests. The authors argue that the drag on the cylindrical net caused by hydrodynamic forces governed by the flow velocity and the net deformation mutually depend on each other.

The present study shows a similar relationship between drag and net deformation, which both increased with the flow speed. The drag on a net depends largely on net characteristics as size, material, structure and solidity, as well as on the flow speed and the angle of attack. Following equation (2), the forces on a solid, rigid structure will increase with the square of the flow speed. We have seen that nylon nets deform in currents, resulting in a change of the net structure, which in turn leads to local changes in the angle of attack. This change will be of different size for different parts of the nets, and deformation was largest close to the surface and at the upstream side of nets (see also Fig. 7). The angle of attack change will always be towards larger angles, which, according Eq. (1), will lead to lower drag coefficients, as C_D is a function of the cosine of the angle of attack. That means that while an increase of the flow velocity leads to increased hydrodynamic forces on the cage, additional drag causes more net deformation. Net deformation, in turn, reduces the drag coefficient of the net, which then lowers the net drag. As a results of these interactions, deformation and drag increase with the upstream flow speed, but the rate of drag increase becomes small when net deformation is strong.

4.3.2 FLOW SPEED REDUCTION INSIDE FISH CAGES

Method I has previously been used to calculate hydrodynamic forces on net structures (e.g. (Lader, Enerhaug, 2005; Lader, Fredheim, 2006). (Lader, Enerhaug, 2005) compared results based on calculations similar to method I with laboratory tests with a cylindrical net. They present a good fit to experimental data at flow speeds below 0.2 ms^{-1}. However, at faster flow speeds they found an increasing overestimation drag. The present study does not allow a comparison with the measured drag below 0.3 ms^{-1}, but at intermediate flow speeds the difference between measured and calculated drag in this study based on eq. (1) (Aarsnes, et al., 1990) is higher than that presented by (Lader, Enerhaug, 2005), while it is slightly lower when based on eq. (2) (Kristiansen, Faltinsen, 2012). These models to calculate drag are partly based on model tests, and differences between these tests and differences in the numerical approach may cause discrepancies between the models. At low flow speeds there is little difference of C_D and therefore drag calculated based on eqs. (1) and (2), but differences between the models increase rapidly with flow speed. Using a static flow speed reduction inside net cages of 20 % across all flow speeds lead to substantial overestimation of drag using method I for both models to calculate C_D. Already at a flow speed of 0.3 ms^{-1}, method I overestimates drag by 46% (based on eq. (1)) and 29 % (based on eq. (2)). At higher flow speeds the discrepancy between measured and calculated drag quickly increased. That means that not all factors influencing net drag are properly represented in the model.

Method II assumes a variable, flow speed dependent flow reduction inside the net cage based on measured flow reduction with this cage setup. The change from a single, static flow speed reduction (method I) to a variable, flow speed dependent flow reduction decreased the estimated drag dramatically, and at an ambient flow speed of about 0.3 ms^{-1} the deviation between calculated and measured drag was well below 10%. However, while method II based on eq. (1) lead to a 7 % overestimation of drag, the same calculation with C_D based on eq. (2) underestimated drag with about 8 %. At a flow speed of about 0.5 ms^{-1} drag is overestimated by 20 % (eq. (1)) and underestimated by 17 % (eq. (2)). Drag then increases with flow speed faster than for the drag measurements in this study, and at high flow speeds both models for the calculation of C_D lead to an overestimation of drag. The drag calculation models did not show a decrease in the rate of drag increase with flow speed. The drag models were developed using tests with net panels or model net cages at laboratory scales, including static flow reduction factors based on laboratory tests. The introduction of a variable flow reduction with much decreased flow speed inside net cages at flow speeds from about 0.3 ms^{-1} must have an important impact on drag calculations, as drag depends on the square of the flow speed. The effect of a stronger flow reduction lead to an underestimation of drag at intermediate flow speeds of about 0.3 and 0.5 ms^{-1} for calculations based on eq. (2).

Clearly, none of the drag calculation methods used in this study properly considered all factors influencing drag on a net cage. The calculation models were included in this study not to suggest new methods for the calculation of cage drag, but to illustrate the importance of a good understanding of the flow past net cages in order to implement the hydrodynamics of flexible net cages properly in drag calculation models.

Several laboratory studies found a reduction of the upstream flow speed inside net cages with relevant net solidities of about 10 – 20% (Gansel, et al., 2012; Løland, 1991; Zhao, et al., 2015). Furthermore, (Zhao, et al., 2015) found no difference in the flow attenuation for different upstream flow speed. However, flow attenuation can vary with current speed in the field for both stocked and empty net cages ((Johansson, et al., 2014); Gansel, unpublished data). The model results using a static flow reduction factor (method I) were vastly improved by the introduction of a flow dependent flow attenuation (method II). However, underestimation of drag (method II, eq. (2)) is concerning. Using a static 20 % flow reduction inside net cages seems to be sufficient to avoid underestimation of drag, which would be concerning when using similar calculations for the dimensioning of structural fish farm components. This study shows that a better description and understanding of the flow past net cages is needed to implement properly flow attenuation models for calculations of hydrodynamic forces on net cages.

4.4 OTHER CONSIDERATIONS FOR DRAG ESTIMATION

Both drag calculation methods used in the present study are directly dependent on the angle of attack, and the reduction of the flow speed inside cages due to blockage by the net (in addition to factors that are kept static in this study). However, the partly deterministic nature of eqs. (1) and (2) means that other physical phenomena are accounted for indirectly, such as the small scale flow structure around net strands or flow attenuation around single straight net panels. The hydrodynamics of a section of a larger structure, like a net cage, may differ from that of a single net panel, as neighboring section of the net structure may alter the local flow field. Fluid-structure interaction is complex for flexible net structures (Lader, Enerhaug, 2005), and the interplay of currents, net deformation and forces mutually and constantly influence each other. Even though we adjusted the drag coefficient with regards to the deformation of the cage in different currents and introduced flow reduction as measured for this cage system, methods I and II deviate from measured cage drag. That means that other important phenomena are not properly accounted for. (Gansel, et al., 2012) show streamlines through porous cylinders with relevant solidities. Their tests were at small scales and therefore at much lower Reynolds numbers than those for a commercial fish cage in a current in the range of centimeters per second, but their results demonstrate that the blockage effect of a net leads to flow re-direction along the porous surface. The drag coefficient based on eqs. (1) and (2) is dependent on net solidity and angle of attack. When the blockage of an upstream part of the net cage leads to the re-direction of the current, the angle of attack between the neighboring downstream net section should be corrected for both the net deformation (as in methods I and II), but also for a change in the upstream flow direction. Net deformation and flow re-direction will affect the angle of attack in the same direction. Since the drag coefficient is dependent on the cosine of the angle of attack, slight changes in the latter can strongly affect the drag coefficient. Therefore, flow re-direction due to net blockage is likely to be a factor that may influence net drag.

More advanced numerical models can give better estimates of the drag on distinctly deformed net cages, than methods I and II, especially when they can account for slow drag increase at high flow speeds. However, better understanding of the flow past flexible net cages will help to properly describe and physically accurately implement important physical factors, such as flow attenuation and potentially re-direction, into models to calculate hydrodynamic forces. Future work should focus on the investigation of the flow past net cages in currents, and effects of factors that may be of importance in addition to the net structure. These may include biological factors, such as fish inside cages (e.g. (Chacon-Torres, et al., 1988; Gansel, et al., 2014b; Inoue, 1972) and fouling organisms, that lead to blockage of net apertures (e.g. (Gansel, et al., 2015; Lader, et al., 2015; Swift, et al., 2006).

5. CONCLUSIONS

This study successfully towed a large-scale fish cage using a long tow-rope to create a stable upstream current. Given the right environmental conditions, this method opens for the systematic variation of the flow past large net cages. Since such tests can be carried out in sheltered areas in the field, fish can be introduced into towed cages prior to the experiments. The method therefore seems suitable for investigations the interplay of water flow and fish behavior, as well as for an evaluation of the effects of fish inside cages on water flow.

Relatively simple methods may be used to roughly estimate the drag on flexible net cages, but they seem to yield good results only in a restricted flow speed range. The introduction of a flow speed dependent flow reduction inside net cages vastly improved drag estimates at medium to high flow speeds over more established constant flow reduction for simple deterministic models based on eqs. (1) and (2). However, it also led to underestimation of drag at flow speeds about 0.3 and 0.5 ms^{-1} when using eq. (2) for drag estimation. Future work should include investigations of fluid-structure interactions of fish cages also with focus on the flow field, and especially flow velocities inside net cages.

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Table 1. Summary of net and weight system specifications. Net solidity was measured via image analysis, similarly to the method described in (Guenther, et al., 2010) and (Gansel, et al., 2015).

Cage size and solidity	
Cage diameter [m]	12
Cage depth [m]	6
Net solidity [Sn]	0.27

Component	**Type**	**Dimension**
Net, sides	Nylon (Egersund Net Nr 20)	15 mm (half mesh), 2 mm (thread diameter)
Net, bottom	Nylon (Egersund Net Nr 20)	15 mm (half mesh), 2 mm (thread diameter)
Top rope	Danline	14 mm
Main rope	Danline	14 mm
Bottom rope	Lead-line	0.5 Kg
Cross rope	Danline	14 mm
Side rope	Danline	14 mm
Ropes holding weights	N/K	10 mm
Weights	Concrete	8 x 35 kg in water

Table 2. Time intervals, flow speeds and deformation of the fish cage net. The depth and deformation is in percent of the un-deformed cage depth and volume in still water. Standard deviation of speed is expressed as percentage of the speed, and as the original figure in ms^{-1} *(in parentheses).*

Configuration	**Time interval [min]**	**Nominal speed [m/s]**	**Total speed measured [m/s]**	**Speed SD**	**Depth [%]**	**Volume [%]**
Floaters	10	0.2	0.215	31 % (0.067)	n.a.	n.a.
Floaters	10	0.3	0.243	31 % (0.075)	n.a.	n.a.
Floaters	10	0.5	0.485	13 % (0.063)	n.a.	n.a.
Floaters	10	0.7	0.673	11 % (0.074)	n.a.	n.a.
Floaters	10	1.0	0.962	6 % (0.055)	n.a.	n.a.
Floaters + net	10	0.2	0.156	14 % (0.021)	95	86
Floaters + net	10	0.3	0.312	8 % (0.025)	81	75
Floaters + net	10	0.5	0.509	6 % (0.030)	62	59
Floaters + net	10	0.7	0.732	8 % (0.055)	45	44
Floaters + net	10	1.0	1.056	7 % (0.073)	34	33

Table 3. Measured drag on the net and drag calculated by methods I and II in kN and expressed as percentage of the measured drag. Under Aarsnes C_D was calculated based on (Aarsnes, et al., 1990), under Kristiansen & Faltinsen C_D was calculated based on (Kristiansen, Faltinsen, 2012).

Velocity [ms^{-1}]	**Measurements [kN]**	**Method I**		**Method II**	
		Aarsnes [kN]	**Kristiansen & Faltinsen [kN]**	**Aarsnes [kN]**	**Kristiansen & Faltinsen [kN]**
0.156	n.n.	0.735	0.776	0.817	0.862
0.312	1.865	2.715	2.405	1.99	1.707
0.509	3.119	6.24	4.715	3.733	2.583
0.732	3.902	10.758	7.278	6.296	3.828
1.056	3.833	19.074	12.123	11.15	6.324

Velocity [ms^{-1}]	**Measurements [kN]**	**[% of Measurements]**	**[% of Measurements]**	**[% of Measurements]**	**[% of Measurements]**
0.156	n.n.	n.n.	n.n.	n.n.	n.n.
0.312	1.865	146	129	107	92
0.509	3.119	200	151	120	83
0.732	3.902	276	187	161	98
1.056	3.833	498	316	291	165