Submerged flexible circular porous structures in currents and waves
FLEXISTRUCT

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Fish farmers are expressing the need and ambitions to move operations to exposed sites, where high currents and waves occur regularly. While there are major potential benefits of fish farming in such areas, there are also considerable bottlenecks that must be overcome to ensure economic profitability and ecological sustainability. One of the main Challenges is the one related to the farm structural integrity. According to the farmers mandatory reports filed to the Norwegian Directorate of Fisheries following escape events, structural failure is the dominating cause of escapes (68%) from Norwegian fish farms. Structural failures may be generated by severe environmental forcing or human errors. Adapted solutions are required to reduce risks in areas with high currents and waves, as the loads from the environment will increase in magnitude and make working conditions more difficult for the farmers. There is a strong need to investigate different solutions to ensure the structural integrity of the farm system as a whole and the welfare of the fish. Fish cages have to handle strong currents and large waves. Operators have been utilizing and improving technologies and methodologies, based almost entirely on the use of floating cages. Novel or alternative technologies have also been developed including the use of submerged systems, particularly in open ocean situations: these commercial cages design exist for different sea exposure, but have mixed success. In these experiments focus, is on the adaptation of the plastic collar floating cages: studies are required to develop reliable design of fish farm structures in exposed sites.

1. RELEVANCE AND SCIENTIFIC AIM AND BACKGROUND

Moving operations to areas where currents and waves are large can reduce the environmental impacts of modern fish farming, yet introduce challenges for the cultured fish including swimming in the currents and in reduced cage volumes resulting from net cage deformations. Fish welfare is highly dependent on both internal volume of the net structure and the currents. The main objective of this project is to study the fluid structure interaction that occurs when a flexible, structure like a net cage is immersed in a flow with waves. The aim is to get a better understanding of the response of flexible porous structures under intense and extreme loadings, and find benchmarks to improve the ability to model such interactions numerically.

Most structures in nature are flexible and manage to deal with flows: for example leaves by changing their shape will maximize their surface area in order to capture an optimum sunlight (**Vogel 2009**). Any large body anchored in a flow, will generate vortex shedding in its wake: these vortices will interact with the body and change the loading on it. This problem becomes more complicated when the body is flexible.

Drag reduction by reconfiguration. The research will focus on the deformation of flexible structures in currents and waves. The physics to be studied are similar to the mechanism of reconfiguration of broad leaves subjected to wind loading (Schouveiler & Boudaoud 2006): the shape of the structure changes when the velocity increases or when the structure stiffness decreases. This reconfiguration leads to a decrease in the drag coefficient, and it is clearly shown by Vogel (1989) and Gosselin et al. (2010), that the drag growth with velocity for a flexible bluff body is much slower than the classical ridgid body law, $F \propto U^2$, where F is the drag force and U is velocity. Vogel proposed $F \propto U^{2+\vartheta}$, where ϑ is the Vogel exponent. The only published work on this topic (Lader & Enerhaug 2005) showed that the drag on net structures does not increase as U^2 due to flexibility, but in this study no waves were involved.

Effect of waves and currents on a net cage. Nearly all cages used in exposed areas in the Norwegian salmon farming industry are of the *"gravity"* type . These cages have a surface collar structure from which a net is hung. Gravity cages do not have rigid nets and 'bagging' deformation occurs in strong currents and decreases the total cage volume. Cages deform in currents largely by a deformation of the front and back walls, and thereby also lifting the bottom netting (Aarsnes *et al*. 1990). As reported by Lader *et al*. (2008), current speeds of 0.13 - 0.35 m s^{-1} at two full-scale farms caused cage volume reductions of up to 20- 40% and resulted in the cage bottom being lifted significantly. In extreme cases, where nets are severely deformed during storms that generate currents >1 m s^{-1}, mass mortalities of up to 40 tonnes of fish in a cage have occurred. Flow through and around a cage is influenced by factors such as cage design, cage layout, fish movements, flow conditions at a site and local topography (Klebert *et al*. 2010), but descriptions of these patterns and their correlations have not been field-tested with enough detail to provide useful benchmarks. Numerical simulations and small-scale laboratory tests show that current speed and net porosities can affect the internal hydrodynamics of sea-cages (Shim *et al*. 2009; Gansel *et al.* 2010).Norwegian classification system of degree of environmental exposure for fish farm sites, using significant wave height (H_s), wave spectral peak period (T_p) and current (V_c) (Table 1).

Table 1 : Norwegian aquaculture site classification scheme for waves and currents

Wave	H_s (m)	T_p (s)	Degree of exposure	Current	V_c (m/s)	Degree of exposure
A	0.0-0.5	0.0-2.0	Small	a	0.0-0.3	Small
B	0.5-1.0	1.6-3.2	Moderate	b	0.3-0.5	Moderate
C	1.0-2.0	2.5-5,1	Medium	c	0.5-1.0	Medium
D	2.0-3.0	4,0-6,7	High	d	1.0-1.5	High
E	>3.0	5.3-18.0	Extreme	e	>1.5	Extreme

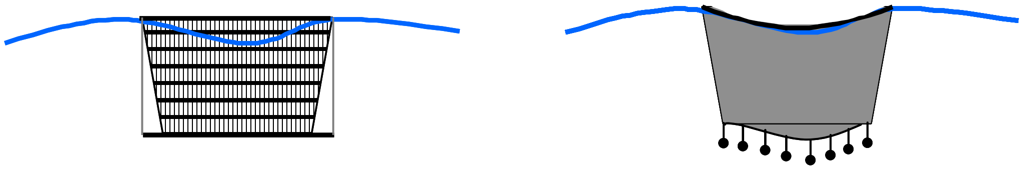
2. MATERIAL AND METHODS

Main objective of these experiments: To investigate the different mechanisms involved in the deformation of flexible structures in currents and waves. The aim of these experiments is to acquire more knowledge on the internal hydrodynamics and deformations of full-scale cages in the medium to extreme environmental classifications for waves (C-E) and currents (b-c).

Approaches, hypotheses and choice of method: Experiments with simple structures have been conducted prior to those at CIEM. Four types of simple structures (flexible plates, flexible porous plates, flexible membranes and nets) have been tested in a small-scale wave flume in Trondheim, Norway. The effects of surface porosity on the hydrodynamic forces and deformation of flexible structures, have been used to determine the appropriate porosities and flexibilities to design the net cages for the experiments at CIEM.

Objective of the experiments at CIEM: To get a better understanding and details of the flow patterns inside and outside a cage in waves and currents to provide useful benchmarks for numerical models.
Background and Problem: Different hydrodynamic load models have been used to calculate the drag and lift forces, and the wake behind structures in fish farms (Aarsnes *et al.* 1990; Løland, 1993), but square cages have been used in this work. Numerical models to calculate the flow field upstream and inside a cage have been developed (Fredheim *et al*. 2003) but are not practical for large net cage systems. More recently, the complexity of flows around single porous cylinders has been studied experimentally (Harendza *et al*. 2009; Gansel *et al*. 2010). Experiments on the interaction between waves and a cage have also been performed, but due to a limited number of measurements, an accurate description of the flow inside and outside the cage is not available.

Research and Solution: These laboratory experiments were planned to study the effects of wave height and period and current speed on the internal and external hydrodynamics of cages. Currently two designs are mainly used (Figure 1): in figure 1 a) a sinker tube is deployed from the surface collar and attached to the lowest portion of the net, a solution currently used to reduce bagging deformations that occurs with the design in **Error! Reference source not found.**b). The weight of the sinker tube affects the total volume of the cage, the flexibility and, depending on the frequencies and heights of the waves, the behavior of the cage. A heavy weight sinker tube will make the total structure more rigid and so less compliant to follow wave shape (Figure. 1a), as opposed to separated weights (Figure. 1b).



a) **b)**

Figure 1 : Influence of the bottom design: a) weight sinker tube, b) separated weights.

During these experiments HYDRALAB at CIEM, Three different designs have been tested (figure 2). During the tests, cage drag and deflection of the bottom rim have been measured with pressure gauges and underwater cameras. Velocity field inside and outside the cage have been recorded with the available sensor systems at CIEM. In the design1 the sinker tube is completely integrated to the net. The design 2 is the old design where some point weight loads are attached to the bottom of the net. The design 3 is the one with the sinker tube suspended from the surface

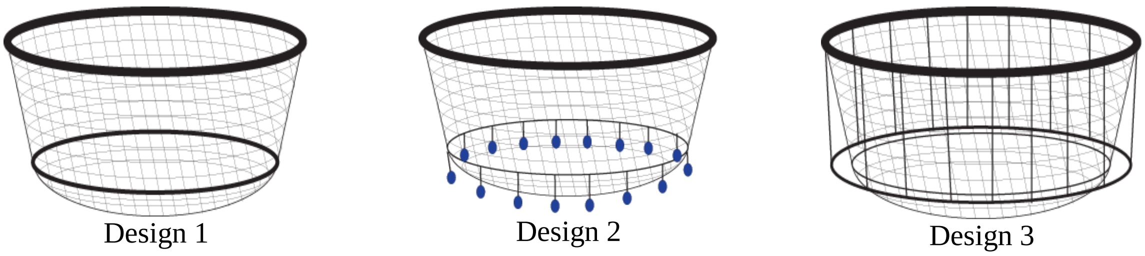


Figure 2 : Three designs tested during the experiments Hydralab at CIEM.

The fish net cages were placed in the CIEM flume Wave tank. Waves are generated at the wave paddle. Interaction between waves and the structure takes place The displacement of the waves as they propagate along the tank are recorded through 13 wave gauges: 8 gauges have been disposed in front of the net cage , one in the cage and 4 on the wake of the net cage. In addition there are 7 ADVs (Acoustic Doppler velocimetry) which record the velocity field around and in the cage and also on its wake. At the end of the flume, a dissipating parabolic beach prevents reflection of waves back towards the structure. Figure 3. shows the positions of the 13 wave gauges (WG) along the flume tank. In this figure the absorbing beach is not represented. During all the experiments, the water depth was kept constant at h = 2.3m during all tests.

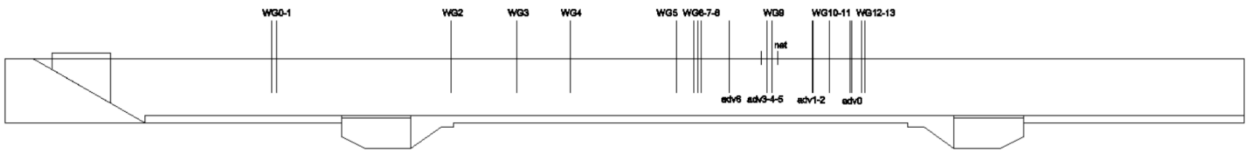


Figure 3 : Positions of the 13 wave gauges along the flume tank at CIEM.

The measured parameters are the time series of the drag force on the net cage, time series with the current velocity field in different locations around the net cage and times series of the wave propagation along the flume. In addition video is used to capture events in the vicinity of the net cage and so the deformation of the cage with current and waves.

The drag force on the cage has been measured with two loads cells through some mooring lines on the front and back of the cage. These loads cells are The S-Beam Jr. (LSB200) from FUTEK, It is a miniature load cell that is able to measure compression and tensile forces in the range of 10 grams to 100 lbs (444 Newtons). These cells are waterproof and very small so induce fewer disturbances to the flow (figure 4).

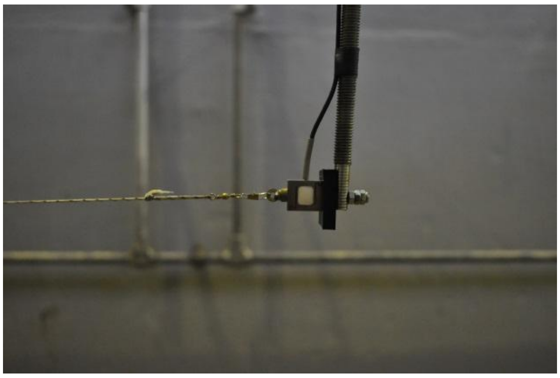


Figure 4 : Picture of the load cell (LSB 200) located on the back of the cage.

The current velocity field was measured with the vectrino velocimeter from NORTEK. The probe consists of four receive transducers, each mounted inside the receiver arm, and a transmit transducer in the centre. The vectrino uses the Doppler effect to measure current velocity by transmitting short pairs of sound pulses, listening to their echoes and, ultimately, measuring the change in pitch or frequency of the returned sound. Sound does not reflect from the water itself, but rather from particles suspended in the water (For that purpose, the level of particles in the water has to be carefully monitored and seeding particles were added when needed).

The resistance type wave gauges used in the CIEM operate on the principle of measuring the current flowing in an immersed probe which consists of a pair of parallel stainless steel wires (the absence of other support reduces the interaction between the measuring device and the incoming/reflected waves). The current flowing between the probe wires is proportional to the depth of immersion and this current is converted into an output voltage proportional to the instantaneous depth of immersion. The output circuitry is suitable for driving both a chart recorder and a data logger Load Cells. All these gauges were calibrated every day prior each experiments.

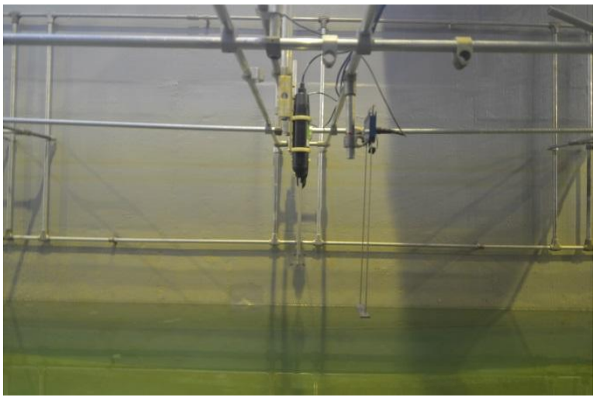


Figure 5 : Picture of the ADV located inside the cage (Right) and wave gauge (Left).

Two mini underwater cameras together with LED Spot lights were placed along the wall of the tank in front and in the back the cage. It gave information about the deformation of the cage submitted to current and waves. And in addition another camera with large angle lens was used through the window outside the tank (figure 6).

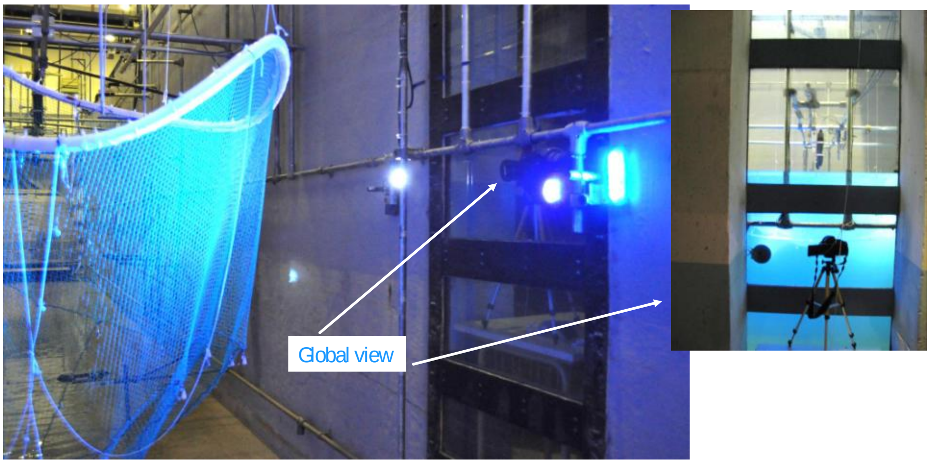


Figure 6 : Picture of the underwater cameras and LED lights and the outside camera.

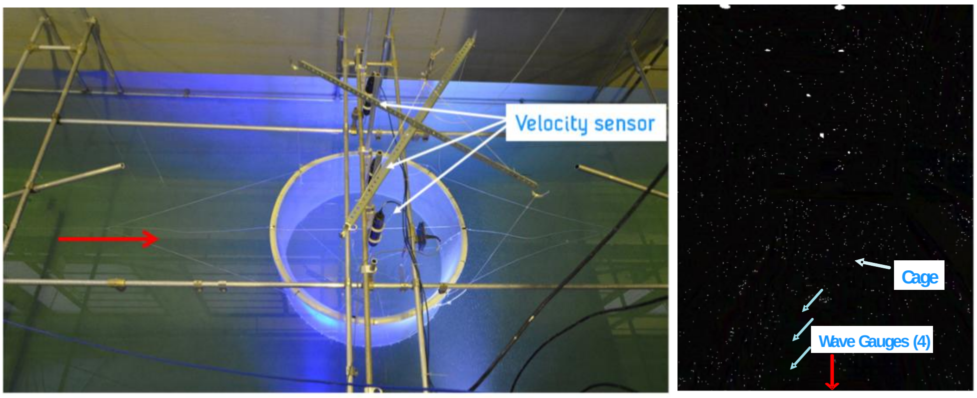


Figure 7 : Picture of the cage in the tank and the sensors mounted at the scaffolding.

3. RESULTS AND DISCUSSIONS

All the three designs reported in figure 2 have been tested with two solidities (Sn1= 0,1072 and Sn2=0,319) . The latest one (Sn2) is considered as a high one which offers large deformation with current flow. All the nets using during these experiments are scaled (in relation to what is used in the sea). Also all the weights, sinker tubes and point weight loads (figure 2) are identical and correspond to a weight of 10548 Kg at full scale.

As mentioned in previously, the deformation of the cages under high currents is a huge concerned in aquaculture and with these experiments it was possible to quantify the effect of the different designs on the deformation.

The figure 8, the deformation for the high net solidity (Sn2=0,319) for the three different designs is described. The current flow velocity which is reported, is the full scaled one. The missing pictures in the series are from interrupted experiments, due to contact between the higly deformed nets and the sensors located in the cage. It can be seen that the design 2 which is the old one in the aquaculture industry , suffered the largest deformation . The use of a suspended sinker tube (design 3) reduces the deformation but from V=0,44m/s the deformed net on the back of the cage is in contact for the rope (chains in full scale). This effect is potentially dangerous for the integrity of the cage as with the time it damages the net which can lead to structural integrity failure. The best case is the design 1with the integrated sinker tube. The volume is kept in good shape till V=0,61m/s and so the potential damages which might occur with the chains in design 3, are discarded.

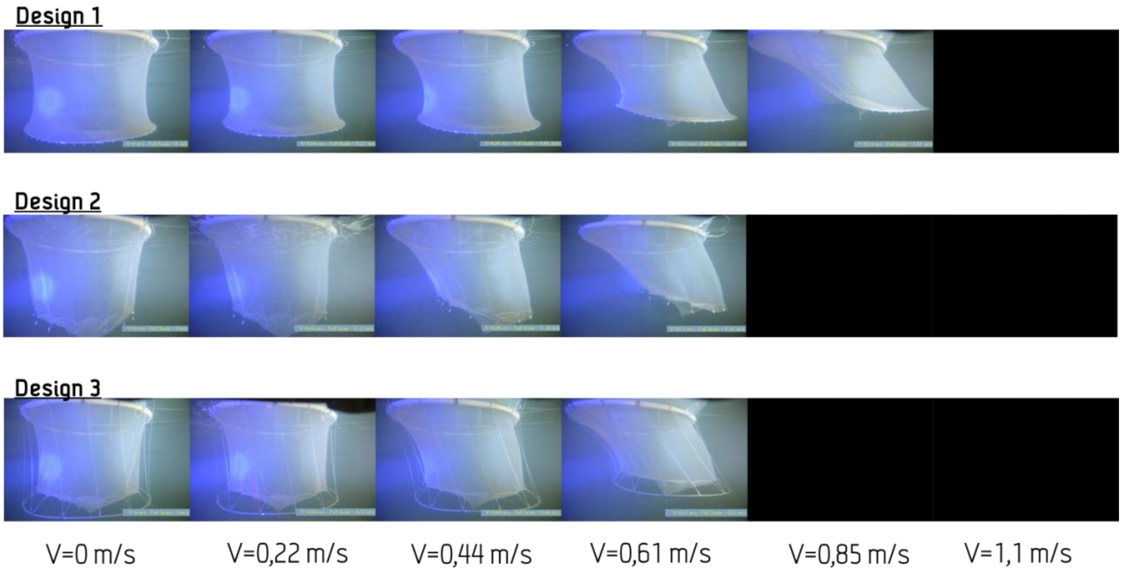


Figure 8 : Deformation for the high net solidity (Sn2=0,319) and the three different designs versus the current full scale velocity.

The figure 9, the deformation for the low net solidity (Sn1=0,1072) for the three different designs is described. As the net solidity is lower than Sn2, less deformation of the net was expected. But the same physics previously described, can be seen: the design 1 offers the best alternative as the volume of the cage is kept in god shape till very high current flow (V=1,1 m/s). While again the design 3, fails from V=0,61m/s as contact between the nets and rope (chains in full scale) which hold the sinker tube from the surface.

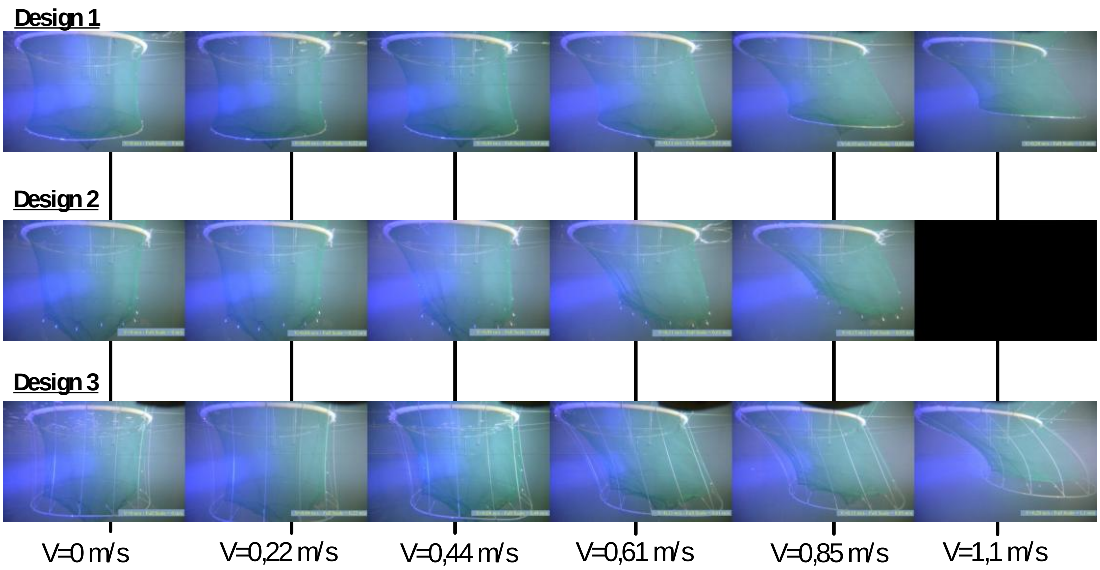


Figure 9 : Deformation for the low net solidity (Sn1=0,1072) and the three different designs versus the current full scale velocity.

During these experiments with current flow, the drag force on the net cage was also measured. The measured forces are reported in figure 10(Sn2) and 11(Sn1). As explained previously, the experiments with high solidity nets give high deformation have to be stopped earlier than those with lower solidity to avoid contact with the sensors located in the cage. The main conclusion that can be done from the measurement, is that the changed in the designs is not really reflected in the drag force on these cages as these are quite similar for a large range of velocities.

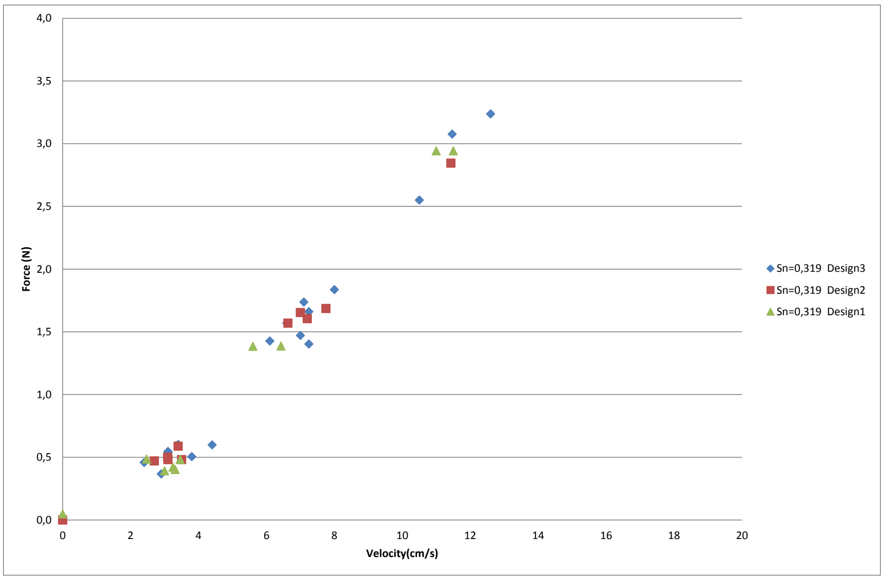


Figure 10 : Drag force on the high net solidity (Sn2=0,319) and the three different designs versus the current velocity in the tank.

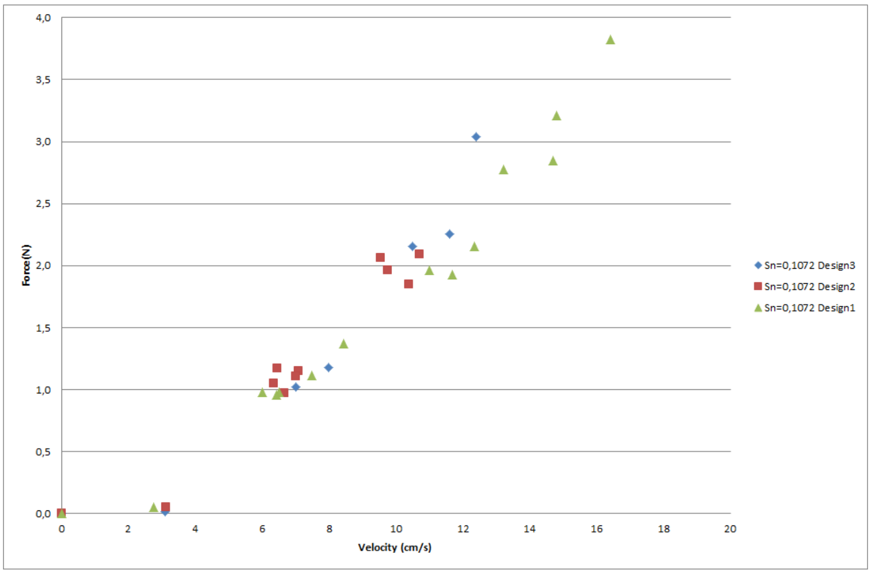


Figure 11 : Drag force on the low net solidity (Sn1=0,1072) and the three different designs versus the current velocity in the tank.

Measurements have been also conducted with waves (T = 1,5s and H=0,12-0,15-0,20-0,25 meters) which respond at full Scale to a wave height of 3,6-9,2 m. In the figure 12, the force measurement for the high solidity (Sn2) and the design 1 (with integrated sinker tube) is reported. The main observation is that for small waves height the current flow is the responsible of the increase of the drag, while for high waves height, the current flow is less important.

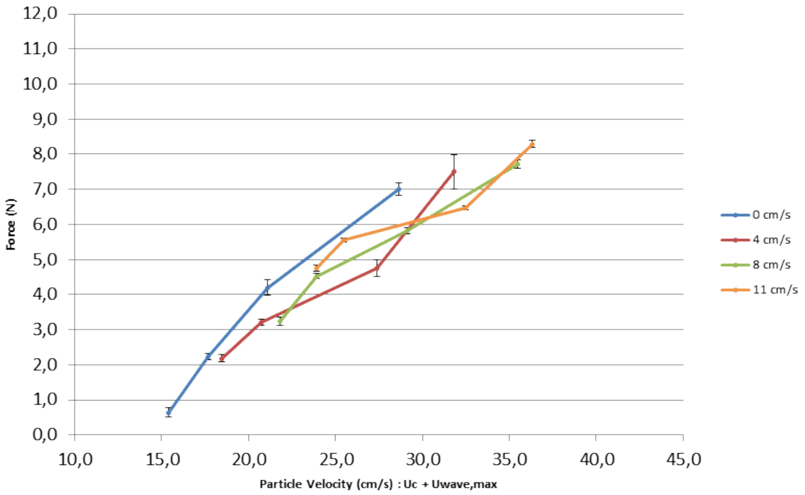


Figure 12 : Drag force on the high net solidity (Sn2=0,319) and the design1 with current velocity in the tank and waves (T = 1,5 s ; H = 0,12-0,15-0,20-0,25-0,30 meters).

4. Conclusion

Through these experiments, it was possible to show the effect of a design of a net cage on the volume deformation. Different designs have been tested and it is shown that the one with an integrated sinker tube (bottom weight ring) offer the best alternative in order to keep a safe volume for the fish when the current flow increase.

Acknowledgement

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