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Experimental study of current forces and deformations on a half ellipsoidal closed flexible fish cage

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ABSTRACT

Closed flexible fish cages are proposed as a new concept in marine aquaculture, replacing the conventional net cages in order to meet ecological challenges related to fish lice and escapes. It is important to understand the response of the cage exposed to current loads. Then more knowledge about forces and deformations on the closed flexible fish cage for different filling levels is needed. A scaled model of a closed flexible fish cage shaped like a half ellipsoid was tested in a towing-tank. Global drag forces and bag deformations were measured for four different filling levels between 70% and 100%, and steady current velocities between 0.04 m/s and 0.22 m/s in model scale, corresponding to Reynolds numbers in the range $Re = 3\text{–}17 \times 10^4$. Findings from the experiments showed that the drag force increased for decreasing filling levels. This increase was caused by a large deformation of the front of the bag affecting the drag coefficient.

1. Introduction

Norway has become the world's largest producer of Atlantic salmon through use of open net structures in the sea. The aquaculture facilities have grown both in size and number. Currently, the industry faces increased attention on environmental challenges related to fish escapes, sea-lice, diseases and pollution. This is despite improvements in technology and operational procedures. The aquaculture industry is under a considerable pressure to introduce technologies and practices that reduce the influence from the aquaculture on the environment (Michael et al., 2010). A possible contribution to the solution is to develop a closed flexible fish cage (CFFC). The main objective of the CFFC is to better restrict and control the interaction between the fish farm and the surrounding environment.

The CFFC is a membrane structure, replacing the net structure. Remaining parts of the fish farm installation such as the floater and mooring system may be used as before. By reusing available components, the CFFC may be easier to put directly into operation at existing sites. By exchanging the net with a tight bag we get a closed compliant submerged structure with a free surface. Few ocean structures exist with large, compliant submerged components. It is therefore presently limited existing knowledge about how CFFCs will respond to external sea loads (Rosten et al., 2013). It is crucial to secure the cage against structural collapse. Therefore, knowledge of the behaviour of the bag when subjected to current and wave loads is vital. The modelling and investigations of sea loads on CFFCs will start with locations in less exposed waters. We will

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Nomenclature

A	projected frontal area
C_D	dimensionless drag coefficient
$\overline{C}_D(\lambda)$	mean drag coefficient for each filling level
D	diameter of the bag
E	Young's modulus
F_D	drag force
F_x	force measurements in x direction
h	max draft of the bag
h_d	deformed draft of the bag
L/r	non-dimensional travelled distance
λ	filling level
ν	kinematic viscosity of the fluid
ρ	fluid density
τ	Froude scale
t_F	thickness of fabric in full scale
t_M	thickness of fabric in model scale
U	towing velocity
V_0	full volume of the bag

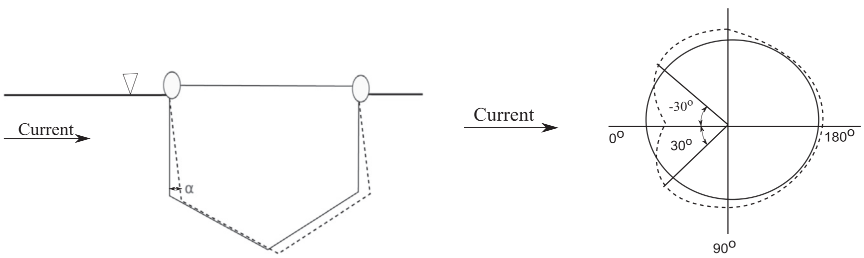
therefore in the work of this paper only consider current loads.

The bag is flexible and behaves hydro-elastically, meaning that the deformation of, and hydrodynamic forces on the bag are closely coupled. Rudi and Solaas (1993) modelled the effect of current forces and deformation, on a full bag pen, which is an early version of the CFFC. They found both global and local deformation patterns. The global deformation of the bag pen was approximated based on moment equilibrium. A symmetric deformation of both the front and the back wall of the bag were found, comparable to deformations of a rigid beam under pressure, see Fig. 1(a). Local deformations of the bag wall were approximated based on the varying pressure distribution around a rigid circular cylinder in steady flow. Due to these pressure variations, the front of the bag was pressed inwards in an area of $\pm 30^\circ$ upstream of the bag, see Fig. 1(b).

The elasticity of the material and the tension in the fabric govern the shape and flexibility of a fabric structure (Løland and Aarsnes, 1994). Flexible containment bags used for transportation of fresh water or oil in the sea are the structures that most resembles the CFFC. For the flexible containment bags, it has been found that the shape and tension are strongly dependent on the filling level, as presented in Hawthorne (1961) and Zhao (1995).

The filling level of the bag is defined according to the theoretical full volume of the bag. The main operational condition of the CFFC will be full, or overfilled/inflated. However, there might arise situations where the bag is in a condition where it is less than full. Strand et al. (2013) and Lader et al. (2015) studied experimentally the effect on filling level on the drag force for different geometries. The experiments were conducted in the small towing tank at the US Naval Academy in August 2012. Strand et al. (2013) analysed the results for a cylindrical bag, and Lader et al. (2015) compared four different geometries: a cylindrical bag with a cone at the bottom, a cubical bag with a pyramid at the bottom, a conical bag and a pyramidal bag. Velocities in the range 0.021–0.127 m/s were studied, giving Reynolds numbers on the range $Re = 1\text{–}8 \times 10^4$. The Reynolds number is based on the diameter, and given as $Re = UD/\nu$. The Reynolds number is a non-dimensional measure of the characteristics of the flow regime, D is the diameter, U is the velocity and ν is the kinematic viscosity of the fluid, here fresh water. They found that the drag forces on all the different geometries increased with decreasing filling levels. However, for the cylindrical and cubical bags the drag forces had a larger increase than for the conical and pyramidal bags. This increase in drag was found to be due to a local deformation in the front, apparent for filling levels less than 100%, affecting the drag coefficient unfavourably. This deformation was most pronounced for the cylindrical and cubical structures. The deformation resembled the local deformation pattern given by Rudi and Solaas (1993), only in a larger scale. For Reynolds numbers ($Re > 4 \times 10^4$) at filling levels below 90% the local deformations in the front described by Strand et al. (2013), Lader et al. (2015) and Rudi and Solaas (1993) could resemble the shape of a regular parachute. Even though the parachute is an open volume, and the CFFC is a closed volume and thereby also dependent on the internal flows and motions of the bag, parallels can be drawn. The drag coefficients found for the cylindrical and cubical bag in Strand et al. (2013) and Lader et al. (2015) were close to the drag coefficient rage found for parachutes and hemispherical cups (Hoerner, 1958).

For Reynolds numbers below $Re \leq 4 \times 10^4$ (low velocities), the bag did not appear to deform, but remained the shape as it appeared for only static pressure (Strand et al., 2013). The shape of the bag in still water for pure static pressure was found



(a) Global horizontal deformation of bag pen, side view. (b) Local deformation of bag in current, top view. The deflection is magnified for illustration purposes.

Fig. 1. Deformations of a bag pen in current, adapted from Rudi and Solaas (1993). (a) Global horizontal deformation of bag pen, side view. (b) Local deformation of bag in current, top view. The deflection is magnified for illustration purposes.