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A MULTIPURPOSE FRAMEWORK FOR MODELLING AND SIMULATION OF MARINE AQUACULTURE SYSTEMS

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ABSTRACT

Research within marine aquaculture has either focused on technology (e.g. farming structures, autonomous systems, harvesting and transport technologies) or biology (e.g. biomass control, feeding process, fish behavior and welfare). Here, we present a computational framework allowing the integrated analysis of these two aspects in a flexible and evolutive way. This framework is called FhSim which was originally developed for the modelling and simulation of fisheries operations and aquaculture structures, but its application domain has been continuously extended through different research projects.

In this paper, we present the basic design principles and functionality of the FhSim framework with the focus on modelling and simulation of marine aquaculture systems. The basic theories and methods used for the modelling of open net cages, closed cages, fish behavior, feeding processes, and ROV operations in net cages are introduced, respectively. It is also shown how the technological and biological aspects of fish farming can be considered in a specialized or integrated analysis. Furthermore, approaches for combining numerical models with monitoring sensor data, techniques for real-time simulation of fish farming operations and the coupling of FhSim with other simulation programs are discussed.

INTRODUCTION

Atlantic salmon (*Salmo salar L.*) is currently the most significant farmed finfish species in marine aquaculture with more than 2,300,000 tonnes produced globally in 2014 [1]. Most of the Atlantic salmon production is conducted in sea cages that are placed in floating fish farms moored to the seabed or the shore. An example of a modern Norwegian fish farm for Atlantic salmon is shown in Figure 1. Sea-based fish farming involves a variety of tasks: feeding, size grading and distribution of fish to maintain acceptable stocking densities, monitoring of water quality and fish welfare, treatment of diseases and parasites, harvesting, net cleaning and structural maintenance. To have a profitable and sustainable production of fish, it is important to have a high degree of regularity in all these operations, especially when moving fish farming to more exposed locations. Most challenges associated with exposed aquaculture operations will require a multidisciplinary approach [2].

Figure 1. An example of large Norwegian fish farm with 15 net cages. Each net cage can have a volume of up to 50,000 m^3 and hold up to 200,000 farmed Atlantic salmons (courtesy: [2]).

SINTEF Ocean aims to produce new knowledge on both the technological and biological aspects of fish farming, and to use this knowledge to help improve the safety, production efficiency, regularity, fish welfare and environmental impacts of fish farm operation. The software framework FhSim [3] has been under continuous development at SINTEF Ocean during the last decades. Originally created for simulating fisheries operations and aquaculture structures, its application domain has been gradually extended through different research projects. In this paper, we present the basic design principles and functionality of the FhSim framework with a focus on modelling and simulation of marine aquaculture systems. We also show how the technological and biological aspects of fish farming can be considered in a specialized or integrated analysis.

OVERVIEW OF THE FHSIM FRAMEWORK

Fisheries and aquaculture systems are often flexible and complex, meaning that such systems often have to be modelled by nonlinear ordinary differential equations (ODEs). FhSim was thus aimed at solving nonlinear systems in the time domain by integrating mathematical models over a period of time, producing time series of output data describing the system response [4]. Complex systems may be modelled mathematically either as a single entity reflecting all system dynamics or as a collection of interconnected sub-models. FhSim has been developed to support the latter approach, though with a focus on relatively few and complex sub-models. This choice was based on optimizing the trade-off between model reuse, simplicity of use and numerical efficiency.

Since its inception in 2006, new features and models have been implemented with the following goals in mind:

Knowledge accumulation: FhSim accumulates results and knowledge generated in projects as sub-model libraries. These libraries are continuously maintained for future reuse.

Embedded usage: Simulations run in FhSim are possible to embed within other applications. For example, it should be possible to design user interfaces decoupled from FhSim, but able to start and monitor simulations, as well as post-process simulation data after simulation termination.

Simulation efficiency: Model development in FhSim focuses on simulation efficiency, rather than modelling simplicity. User friendliness may be enhanced by embedding FhSim within generic, domain specific or task specific user interfaces.

3D visualization: 3D visualization of simulations is integrated, facilitating results analysis, model development and creating informative outputs (e.g. videos).

Decoupled development and usage of sub-models: Familiarity with the external interface of a specific sub-model is sufficient to employ this model in future simulations. This allows for a more decoupled model development process, as a developer will be able to focus only on the code that is being developed at the present time. Furthermore, this allows the use of sub-models containing confidential information without having to disclose the actual code in these models.

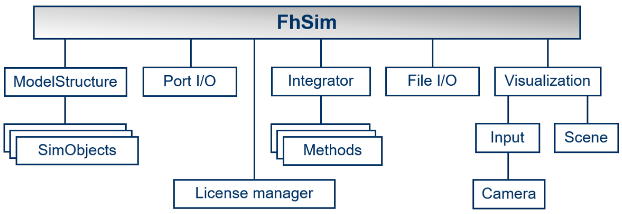

Figure 2. Overview of the FhSim architecture.

Figure 2 presents the key components in the FhSim API, each fulfilling different roles in the simulations:

SimObjects (short for Simulation Objects) are objects which implement different sub-models. Communication between separate SimObjects is facilitated through input/output ports. Each SimObject is responsible for computing its own state derivatives, output ports and visualization. Although the FhSim API is written in C++, SimObjects may be written in any programming language able to compile shared libraries. SimObjects are considered the basic building blocks of a FhSim simulation.

ModelStructure is responsible for presenting a collection of SimObjects as a single model to the rest of the framework. Consequently, this component maintains an overview of all SimObjects, their states and how they are interconnected through input/output ports.

Integrator keeps track of the states of the total system model, and uses the state derivatives presented by ModelStructure to advance these. The state integration is conducted using one of several eligible integration methods, including Euler methods, Heun's method and Runge-Kutta methods. FhSim also facilitates a suitable framework for implementing additional integration methods. Variable time step is supported for integration methods featuring error estimation, such as the classical Runge-Kutta method, whereas methods without error estimates must resort to fixed time steps.

Port I/O facilitates communication between FhSim and other applications or physical equipment. For other SimObjects, these ports appear no different from regular input/output ports. This allows for a seamless integration between external systems and simulation models in FhSim.

File I/O handles all interaction between the model system and files. This includes the parsing and interpretation of input files describing the system, writing to message log files and writing simulation data and results to output files.

Visualization handles aspects regarding visualization which are common to all sub-models, including scene rendering, user navigation and the recording of images to disk. This component is also responsible of calling the visualization methods of each SimObject through ModelStructure at appropriate times. 3D visualization of simulations in FhSim is realized through the open source rendering engine Ogre3D [5].

FhSim represents the overarching main component of the structure and is responsible for wrapping the system model offered by ModelStructure with the Integrator, Port I/O, File I/O and Visualization components. All user interaction occurs through the FhSim component, and it parses the system and integration specifications. Simulation results and outputs are provided through an API, as text files, screenshots, or console messages. A low threshold technique for utilizing multiple CPU cores is implemented, and the size of the internal FhSim thread pool can be set by an integrator option, either as a fixed number, the number of cores available, or the number of SimObjects in the system. The ODE function of each SimObject is then added to a task queue in the thread pool and computed in parallel.

The modularity of the system architecture in the FhSim framework allows a high degree of flexibility, as the user may choose to only include those components deemed necessary to run a particular simulation. In some cases, the use of 3D visualization is important to obtain and understand the desired results. The FhSim core then needs to be compiled using all the elements described in Figure 2. In cases where visualization is not needed, the visualization components may be excluded when compiling FhSim. This produces a compilation which has higher computational efficiency and a lower memory footprint than when visualization is included, a feature which is particularly important for embedded use.

GENERIC MODELS

Sea environment

A sea environment representation is often required to simulate marine systems. FhSim contains implementations of sea environments simulating water current and wave fields (both regular and irregular), and facilitating queries for time dependent and spatial properties such as:

1) Wave elevation at a specified point on the water surface
2) Wave induced pressure at a specified point in the water volume
3) Wave induced particle velocity and acceleration at a specified point in the water volume
4) Ambient current velocity at a specified point in the water volume
5) Sea depth at a specified horizontal position

The sea environments support both Eulerian and Lagrangian linear wave theories and realization of JONSWAP and ISSC wave spectra. The interface to the sea environment objects is generalized to allow different sea states and wave theories to be used without changing the other simulation models. FhSim also supports using data files from the SINMOD [6] oceanographic calculation tool to import area specific 3D current fields and depth conditions into a simulation. Hydrodynamic interactions between the simulation models and with the sea environments are not accounted for in general.

Abiotic environment (factors)

Typical abiotic environments farmed salmon are exposed to include light, temperature, salinity and oxygen levels, which may vary over short (minutes, hours) and long (days, seasons) time scales [7]. The implementation of abiotic environments in FhSim has been restricted to including factors that are known to be fairly independent of the fish, and not strongly affected by current and waves. This enables the development of a simple model definition which is considered independent from the other models, but at the same time may provide temporally and spatially variant data on the defined factors.

At present, the model includes the definition of temperature in centigrade and light intensity (including placement of submerged artificial lights) given in PAR (photosynthetically active radiation) or µE (micro-Einstein), and it is possible to expand the array of environmental factors if needed. These variables may vary with water depth and time, as they are the most realistic axes along which it is most realistic to collect data today (vertical profiling over time).

Hydrodynamic forces

The hydrodynamic forces acting on a simulated body in FhSim are, in general, decomposed into:

1) Excitation forces (wave energy absorbed by the body)
2) Radiation forces (wave energy emitted by the body during movements)
3) Forces due to viscous flow effects such as flow separation and vortex formation

These forces are often specified within each SimObject, but FhSim also contains a generic model for vessel dynamics which includes built-in time-domain realization of frequency-domain hydrodynamic data that are calculated prior to the simulation in FhSim (using e.g. WAMIT [8]). The frequency-domain data must contain the frequency-dependent added mass and damping coefficients for the radiation forces and wave height-to-force amplitude operators for the excitation forces. The transformation from frequency-domain data to time-domain simulation models is accomplished by using the vector fitting system identification method [9] and a linear system adaptation [10] to the convolution integral of Cummins equation [1 1] (fluid memory effects). The excitation and radiation forces calculated by this generic hydrodynamic model are applied to the simulated body at each time step.

An example of simulated sea ice floe interaction with a fishing vessel and waves is shown in Figure 3. In this simulation [12], the generic hydrodynamic model was used for the fishing vessel and each single ice floe. Multi-body hydrodynamic interactions have not been modelled, but can be accounted for (to a certain extent) if relevant frequency-domain data are calculated.

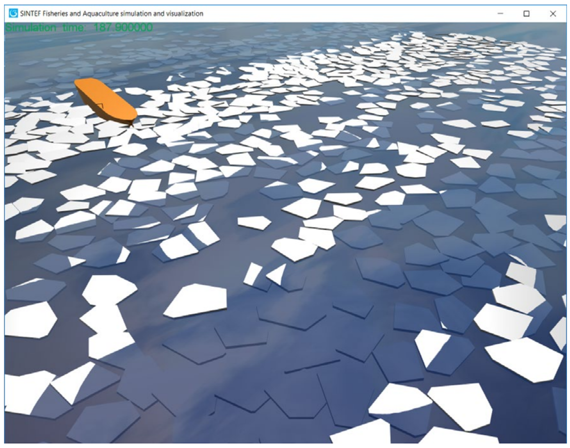

Figure 3. Simulation of sea ice floe interaction with a fishing vessel and waves using the generic hydrodynamic model.

State estimation

FhSim contains a module for system state estimation based on a nonlinear extended Kalman filter [13, 14]. Generic structures can be built from base components like mass and spring objects, with full flexibility regarding sensor configuration. Different numerical implementations of the extended Kalman filter can be applied to the system. These range from the full dynamic Riccati solver suited for small systems with fast and oscillatory dynamic, to more stable solvers with backward Euler and H-infinity type qualities, more suited for large diffusive systems [4].

USE CASES

Open net cages

Aquaculture systems comprised of open net cages are the most common structures used in salmon farming. A typical open net cage consists of a floating collar, a sinker tube, weights and a net structure that contains the fish. Several net cages may be connected to a common mooring frame within one fish farm (see e.g. in Figure 1). Thus, a complete net-cage system includes also moorings, various ropes and chains, buoys and coupling plates (Figure 4). All these components have their corresponding models in FhSim, as described in detail by [15]. Some highlights of these models are also presented below.

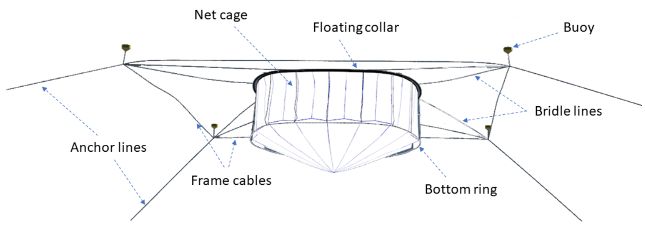

Figure 4. Main components of an open net-cage system.

Floating collar: The floating collar is modelled as a flexible circular ring (1 or 2 tori) with 6 degrees of freedom (DOF) with regard to rigid-body motions. Elastic deformation due to bending is accounted for by Euler-Bernoulli beam theory, while shear forces and torsion are ignored. The structural response of the ring is modelled using the modal superposition principle, where the responses for a finite number of the generalized natural modes are summed to give the total response of the ring. Forces that may act on the ring include restoring buoyancy, wave excitation loads, added mass and additional structural and viscous damping. The derivation of the hydrodynamic forces and modal responses for a floating-ring model can be found in [16].

Net structure: The net structure of the cage model consists of net elements and embedded cable elements for reinforcing the cage. Since the net is flexible, it may deform when exposed to e.g. current and waves. Such deformations are taken into account by considering the net as a collection of triangular elements that are interconnected through nodes, as proposed by [17]. All forces acting on the net and its mass are distributed among these nodes. Two expressions for calculating hydrodynamic forces on a net are available in FhSim: a Morison-type expression with a modified drag law, and the so-called *screen model*. The former is based on Morison's equation and has been validated for certain flow conditions [15]. The latter was originally developed and validated by [18]. Additionally, the effect of flow reduction due to the presence of a net structure in the current is considered according to [16].

Cable elements and mooring lines: All mooring lines and cable elements shown in Figure 4 are modelled as a collection of 6 DOF rigid-bar elements which are connected with axial and angular constraints to provide desired structural properties of a cable, such as bending, axial and torsional stiffness, as well as buckling behaviour under compression forces. These constraints are regularized through an elastic version of the Baumgarte stabilization method [19, 20] to avoid numerical instabilities. Hydrodynamic forces acting on the cable are calculated by a Morison-type expression, and the dynamics of each rigid-bar element are calculated from the sum of the hydrodynamic and constraint forces. A thorough description of the theoretical and mathematical background for the cable model in FhSim can be found in [20].

Sinker tube: The sinker tube (or bottom ring) is connected to the net structure to keep it submerged. It is modelled similarly to cable elements but has higher mass and stiffness, with both its endpoints connected to form a continuous cable structure.

By combining the aforementioned models in FhSim, various net-cage configurations can be simulated. Figure 5 shows an example of simulated eight open net cages in the fish farm shown in Figure 1.

Figure 5. Simulation of a fish farm consisting of eight open net cages in FhSim.

Closed fish cages

Floating closed containment structures for Fish farming, referred to as closed cages, are structures containing a water volume for fish production that is enclosed from the ambient water. Closed cages are currently emerging as an attractive alternative to open net cages for salmon farming in Norway. One motivation for using closed cages is to improve the fish health and welfare and thus farming efficiency, by having better control of water quality inside the cage. The risk of parasite infections (e.g. sea lice) is also reduced when using closed cages by pumping the inlet water from water depths of about 20 m or more where sea lice is less abundant than near the surface. Furthermore, farming in closed cages also enables the collection of waste and deposits resulting from the production, such that the negative impact on the local environment is reduced.

From a structural point of view, closed cages can be divided into three groups based on the stiffness of the structure walls: 1) Flexible cages (neglectable bending stiffness in the walls, i.e. some sort of fabric), 2) Semi-flexible cages (the walls are stiff, but will deform significantly in current and waves, e.g. glass reinforce plastic) and 3) Rigid cages (the walls are so stiff that deformation is neglectable). Most of the proposed concepts for closed cages are either flexible or semi-flexible. Initiatives involving rigid cages in concrete are also likely to emerge in the near future.

A finite element (FE) model, based on so-called rotation-free (RF) shell elements [21, 22], has been implemented in FhSim for simulating closed cages. RF shell elements belong to a family of flat shell elements formed by the superposition of a membrane element and a plate bending element. Compared to conventional shell formulations, RF shell elements do not include any rotational degree of freedom. Instead, constant curvatures are approximated from the out-of-plane displacements of a patch of usually four triangular elements. The main merits of the RF shell elements are therefore the reduction in the number of DOFs and, for nonlinear formulations, the absence of all difficulties related to large rotations [23, 24].

This structural model, coupled with a simplified hydrodynamic model for the discharge of contained water, has been applied in a study on the drainage and collapse of a closed flexible cage (see Figure 6 and [25]). To solve the fluid-structure interaction problem, an implicit time integration method (HHT-α method [26]) was adopted (Figure 7) for this specialized analysis, although FhSim, in general, only supports explicit time integrations. The adapted numerical integration was conducted within a dedicated SimObject for the closed cage and synchronized with other SimObjects (for instance the floating collar) involved in the simulation. The simulation results showed good agreement with physical model tests, in terms of the structural deformation and the drainage time (see Figure 6).

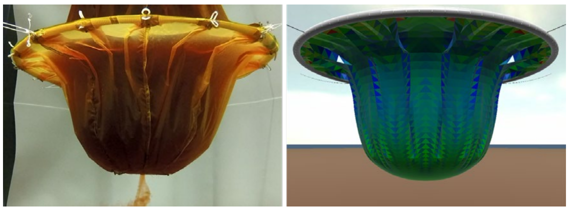

Figure 6. Experimental and numerical study on the drainage and collapse of a closed flexible cage. Left: model test, right: numerical model in FhSim.

The problems of hydroelasticity and sloshing are important when considering the wave response of closed semi-flexible and rigid cages (see Figure 8 and [27]). A multimodal method [28, 29], using the Fourier (modal) approximate solution of the free-surface elevation with time-dependent coefficients, has been implemented in FhSim to simulate nonlinear sloshing in a closed rigid cage (see Figure 8), while the external wave excitation and radiation forces are calculated using the generic hydrodynamic model (see the "*Hydrodynamic forces*" section). It is also possible to use the aforementioned FE model to simulate the elastic deformation of closed semi-flexible cages and the coupling with internal flows which can be modelled using e.g. the harmonic polynomial cell (HPC) method [30] or smoothed particle hydrodynamics (SPH). This work is still ongoing.

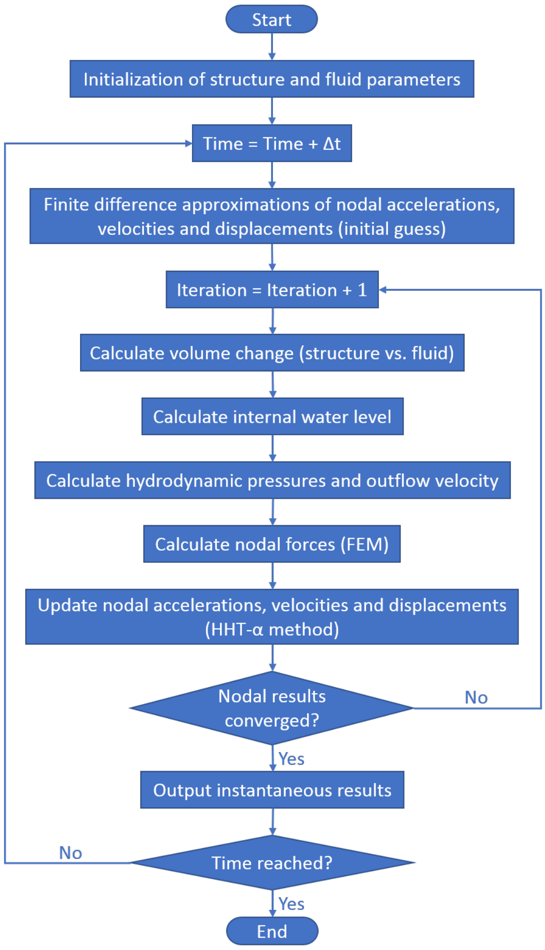

Figure 7. Flowchart showing the numerical simulation procedure of the drainage and collapse of a closed flexible cage [25].

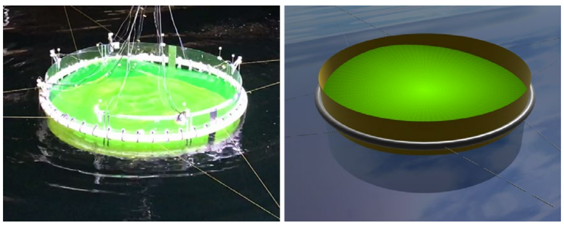

Figure 8. Experimental and numerical study on the seakeeping behavior of closed cages. Left: model test (semi-flexible), right: numerical model in FhSim (rigid).

Fish behavior and energetics

The term "fish performance" generally includes the growth and survival of fish. Maintaining good fish performance is central to any endeavor aimed at fish production as it directly pertains to the biomass development in the farm. Being able to monitor performance parameters throughout a production cycle is desirable, as it facilitates decisions related to cage management and operations based on the status and development history of the fish population. The behaviors of fish also reflect how they respond to different stimuli and is often related to welfare or health. Outputs from behavioral observation may therefore be essential for decision support regarding cage operations, especially when monitoring feeding activity and during critical operations such as crowding. In the fish farming industry, most behavioral observations are made either through direct visual inspection, or by using surface camera, underwater stereo video camera, sonars and echo sounders [31]. Using mathematical models as a supplement to sensor technology and monitoring tools may improve the ability to capture the states and conditions of the fish behavior and energetics, and to provide a holistic view of the state of fish population.

A dedicated model for fish performance in net cages has been implemented in FhSim. The fish performance model is individual based, able to simulate full-scale fish populations (e.g. 200,000 individuals) in real time, and divided into three modules: fish behavior, feed distribution and energetics.

Much of the simulated behavioral expression is based on spatial and temporal behavioral responses toward containment (i.e. net or tank walls and bottom, water surface), feed, temperature, light and other individuals, and was adapted from an existing individual based model of salmon behavior originally developed and validated by [32, 33]. To adapt the spatial response scheme to a more complex external environment, it also had to be expanded with active responses toward prevailing water currents (see Figure 9 and [34]). The model also contains a detailed representation of feeding behavior, where an internal state machine determines if the fish is oblivious of feed ("Normal" state), knows of the presence of feed but has no feeding motivation ("Satiated"), has detected feed and is motivated ("Approach"), or has captured and is processing and ingesting a pellet ("Manipulate"). This model is based on an existing feeding model originally developed and validated by [32, 35], and the transitions between states are managed by probability functions based on the feed concentration in the immediate proximity, local gradients in feed concentration, and the present energetic state of individuals.

To simulate feed pellets and present the individual fish with a spatially and temporally dispersed feed distribution pattern (see Figure 10), an existing particle distribution model originally developed and validated by [36, 37] has been adapted and implemented in FhSim. It is integrated with a surface feed spreader model and can account for pellet reduction due to fish ingestion and the influence from sea environments. This offers new possibilities in simulating the effects of variations in water current and possibly implementing support to incorporate the effects of wind and waves on pellet advection.

The energetic module of the fish performance model is based on an existing Dynamic Energy Budget (DEB) model for salmon growth [35]. DEB model theory features a set of assumptions of how organisms of all types acquire, store and utilize energy [38], and has been proven suitable for modelling the energetics of several different aquatic animal species (see e.g. [39-41]). Although the DEB model has relatively slow dynamics, it is run with a short time step matching the fish behavior model in this setup. This way the feed ingestion rate input to the DEB model can be governed by the simulated feeding behavior [35].

To improve simulation efficiency, a simplified net-cage model was implemented and integrated with the fish performance model. Although the net structure has been simplified, the net-cage model still uses a *screen model* [18] to calculate hydrodynamic forces, and the simulated cage deformation showed good agreement with the experimental result [42] (see Figure 11). This integrated model also offers new possibilities in simulating the influence of fish movements on the hydrodynamic forces acting on the net [42].

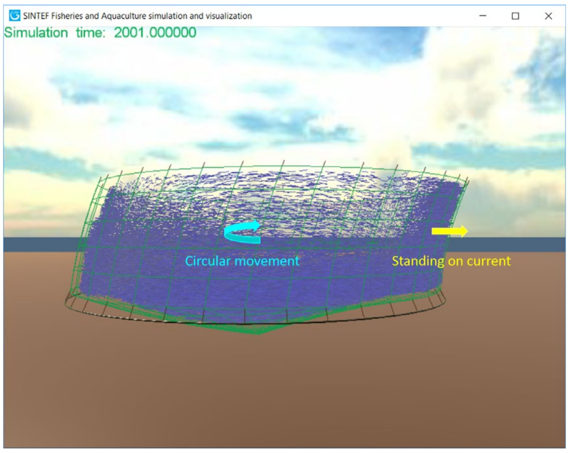

Figure 9. Simulation of fish behavior in water current (a mixed fish swimming behavior was also observed by [34] in the same current and cage environment).

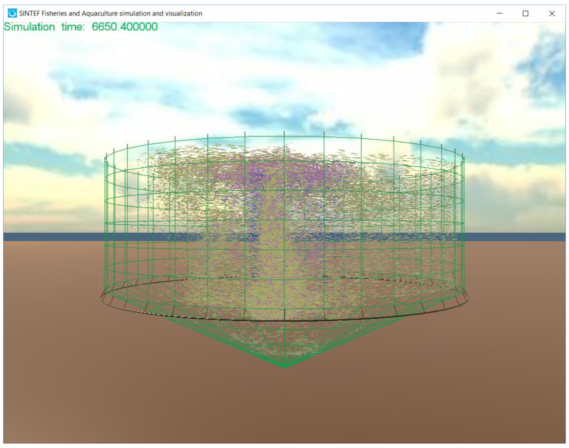

Figure 10. Simulation of feed distribution (marked by blue) and feeding behavior of 50,000 individual fish (marked by yellow, fish that are actively feeding are marked by purple).

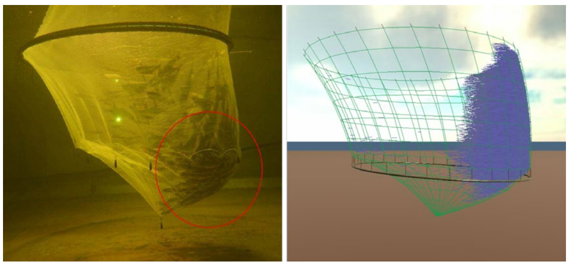

Figure 11. Plots showing a comparison between the simulated cage deformation (right, with simplified net structure) and the experimental result (left, courtesy: [42]).

ROV operations in net cages

In earlier days, most of the necessary underwater actions at fish farms were conducted by divers. Today it has become common to use Remotely Operated underwater Vehicles (ROVs) for tasks such as net inspection and cleaning, greatly reducing the risks of personnel injuries.

A model of a ROV and a GNC (Guidance, Navigation and Control) [42] system for aquaculture net inspection has been implemented in FhSim. The ROV model describes the vehicle dynamics in 6 DOF, based on the vehicle inertia and the forces from hydrodynamics and thrusters. Hydrodynamic forces are calculated based on linear potential flow theory with additional viscous damping, and are derived together with inertia forces and moments in a SimObject representing the ROV frame. The ROV model is equipped with a number of thrusters which are modelled as separate SimObjects. Each thruster calculates its thrust forces in 6 DOF based on thruster placement, attitude and rotational speed.

The GNC algorithms consist of a state observer for estimation (see also the "*State estimation*" section) of velocity and position, motion control algorithms which calculate forces and moments, thruster allocation algorithms which calculate rotational speed for each thruster based on commanded forces and moments, and a guidance system for calculation of desired velocity and position. Among the different guidance and control systems developed for the ROV in FhSim, the one allowing the ROV to automatically traverse a net cage for inspection purposes is the most relevant for aquaculture operations. In addition, a model of Doppler Velocity Log (DVL) can be used to provide the guidance system with the necessary information for calculating the desired ROV position relatively to the net-cage walls (Figure 12).

The GNC system in FhSim can be interconnected with a real ROV (see e.g. Figure 13, and in [44]) through the serial port. The ROV model can also be controlled by external GNC algorithms (e.g. in MATLAB & Simulink) using a TCP/IP (Transmission Control Protocol/Internet Protocol) interface. These modules have been tested and used in field missions at SINTEF ACE, which is a full-scale laboratory facility (see Figure 1 and Figure 13) designed to develop and test new aquaculture technologies.

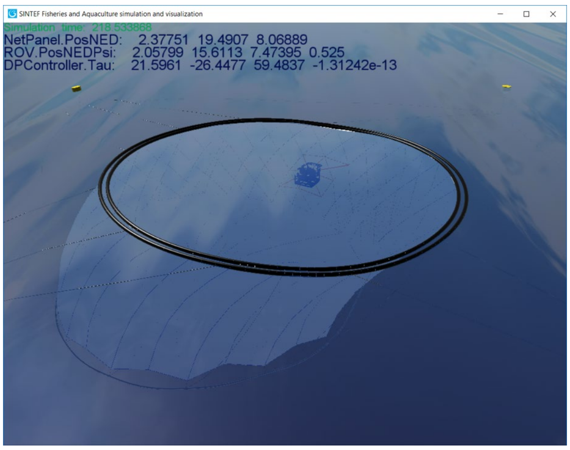

Figure 12. Simulation of a ROV (1:3 visualized) inspecting a specified net panel of the cage.

Figure 13. A ROV used in navigation along aquaculture net pens with hydroacoustic instruments (courtesy: [44]).

FUTURE IMPLEMENTATIONS

The FhSim framework has proven to be a valuable tool for many specialized analyses, such as large deformations of closed flexible cages, ROV operations in net cages and feeding behavior and energetics of individual fish. It also allows an integrated analysis of hydrodynamics, structural response and fish behavior (e.g. Figure 14), which provides new and unique possibilities for a more realistic modelling and simulation of marine aquaculture systems. However, there are still many uncertainties and knowledge gaps that should be addressed for this kind of integrated analysis, such as fish swimming behavior in waves, the effects that fish movements exert on the surrounding water and the influence of underwater operations on the fish. All these aspects will again require specialized analyses which are not discussed here. Some highlights and future modifications of the FhSim framework itself are presented below.

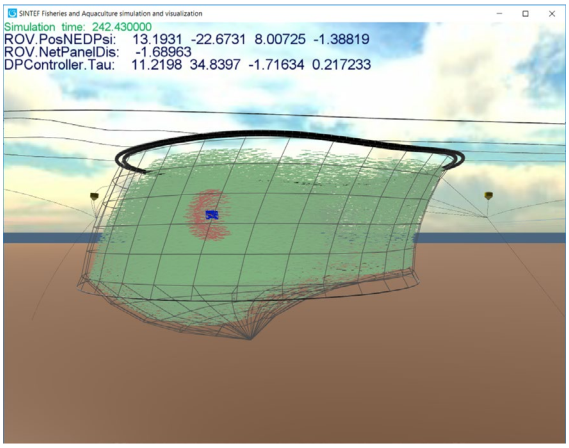

Figure 14. Simulation of fish behavior with a complete net-cage system in current and waves.

Techniques for real-time simulation: Simulation and analysis of slender structures with low bending stiffness and a high modulus of elasticity is a recurring problem in many engineering fields, and there are well known numerical challenges with such simulations when considering performance versus fidelity. FhSim contains a framework (i.e. an extension of the aforementioned cable model) addressing these issues, in which a slender structure is modelled as a collection of 6 DOF rigid elements connected with axial and angular constraints to provide desired structural properties. High-frequency and small-scale dynamics are filtered out using a novel technique based on the Baumgarte stabilization method [19, 45], where the inertia matrix and the system forces are modified based on the constraint pattern. This allows the integrator to take much longer time steps, and the net effect is a faster simulation. In addition to the mechanical constraints, this framework supports collision detection and calculation of collision forces as additional constraints, where a space partition algorithm is used for fast detection of object contact, and the same dynamic filter method is used to apply contact forces. The technique allows for fast simulation of cables with both bending and torsional stiffnesses, as well as full self-collision. It has also been used for real-time simulation of fish performance in net cages (see also the "*Fish behavior and energetics*" section), in combination with a simplified net-cage model (see e.g. Figure 9).

There are still challenges with the simulation of a complete net-cage system (e.g. Figure 14) in real time, because the existing model for floating collar and the connections between different cable elements tend to cause instability problems when an unusually longer time step (e.g. in the order of 0.1 second) is used. One possible solution would be to make a fully integrated model (or system matrix) including all structural components, in combination with the dynamic filter method mentioned above. This integrated net-cage model may be developed for real-time simulation of fish farming operations when detailed structural analysis is not the main focus.

Training simulators used in the maritime and offshore industries are typically based on numerical models that provide the users with a virtual environment where potential work tasks and critical operations may be simulated and trained upon prior to live executions of these tasks or operations. Similar solutions for training personnel for fish farming operations would be possible using numerical models able to realistically predict the influence of such operations on the fish and the farming system. The models (e.g. net-cage systems, feed barges, well boats, ROVs and fish behavior) developed in FhSim, in combination with the aforementioned techniques for real-time simulation, are relevant candidates for the future development of such solutions.

Data assimilation: FhSim contains a framework for system state estimation based on a nonlinear extended Kalman filter (see also the "*State estimation*" section). By using this framework, a numerical model can be combined with sensor data to create a more realistic estimate of the actual system. The current state estimate is advanced forward in time through the numerical model and is continuously updated to the best possible fit to the sensor data. This method has been tested and used in state estimation for fishing trawl systems that are equipped with a number of different sensors [4]. Other cases, such as state estimation for net-cage systems are also under development.

However, features such as individual fish swimming behavior and energetics are typically difficult to quantify using conventional solutions and observer structures based on established methods (e.g. Kalman filters). The ability to monitor the states of the caged fish population through sensors is also diminished as the production units and contained fish populations increase in size. There is therefore a need for looking into how the different monitoring sensor data and predictive models may be combined to provide a more holistic view of the behavior and biomass development of caged fish populations. This is a central topic in the Precision Fish Farming (PFF) concept (see Figure 15 and [31]), which seeks to advance fish production methods from being predominantly experience based to becoming more knowledge and technology based. It would also be a core functionality of the FhSim framework with regard to future applications.

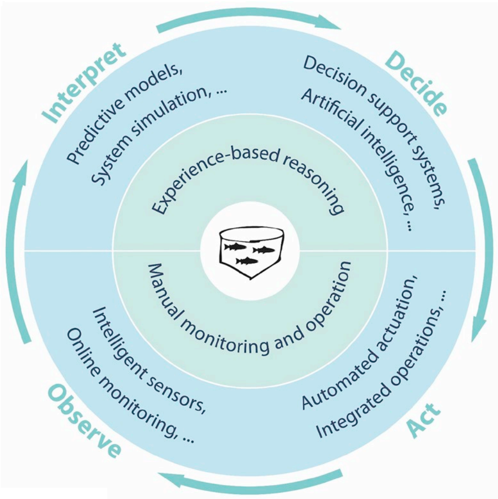

Figure 15. A cyclical representation of precision fish farming (courtesy: [31]).

Model exchange and co-simulation: Simulations run in FhSim are able to communicate with other software packages through the TCP/IP interface or the Data Distribution Service (DDS) that have been implemented as dedicated SimObjects in FhSim. Standards such as the Functional Mock-up Interface [46] have also been considered for model exchange and co-simulation between FhSim and other simulation tools (e.g. SIMO/RIFLEX/SIMA [47]), as the emerging new concepts of marine aquaculture systems will require a variety of specialized models for hydrodynamics and structural analyses (see e.g. in [48-54]).

CONCLUDING REMARKS

The research work presented in this paper demonstrates the potential of developing a multipurpose framework for both specialized and integrated analyses of marine aquaculture systems, and to help in producing new knowledge on both the technological and biological aspects of fish farming. When using this framework (i.e. FhSim), experts may focus on their special field of competence while taking advantage of verified models made by experts within other topics which, in turn, allows integrated analyses of complex systems comprised by models from different domains.

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