Model Tests and Operational Optimization of a Self-propelled Open-ocean Fish Farm

by

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Abstract

The cage production of marine finfish is a well-established method of commercial aquaculture. To date, nearly all of this activity is confined to near-shore waters offering some measure of protection from environmental extremes. Concerns about the environmental impact of discharges from these operations and user conflicts has hampered the growth of this industry worldwide. New cages are being developed by industry that can withstand open-ocean exposure. This will greatly increase the opportunities for industry expansion and reduce user conflicts. The environmental concerns will also be reduced as the energy associated with these exposed sites will help in the dispersion of cage discharges. However, as long as a fish farm is associated with a specific site, concerns will remain over its impact on the seabed below.

This paper discusses a new concept in open-ocean fish farming - The Ocean Drifter. This system is an adaptation of the Sea Station™ cage manufactured by Ocean Spar Technologies® of Bainbridge Island, Washington, U.S.A. Unlike conventional operations, Ocean Drifter is not anchored. It would drift with ocean and coastal currents but have a capability for self-propulsion. The approach is particularly suitable for locations which experience reciprocal tidal currents or gyres. In such cases, a general operating area could be maintained with only minor use of propulsion. Windage and current shear would provide sufficient water exchange for the maintenance of a good growing environment. The current assisted movement of Ocean Drifter, combined with brief anchoring, could be used to exploit the movement of optimal temperature with season or allow the delivery of a crop to a convenient location for harvesting. Ocean Drifter could be designed to be manned or to operate autonomously.

Model tests on Ocean Drifter have recently been carried out by Massachusetts Institute of Technology (MIT) at the David Taylor Model Basin (DTMB) in Bethesda, Maryland. Drifting and self-propelled operations were simulated in calm water and in waves. The results of these tests are reported in this paper. Motions and internal loads of the 1/10 scale model are analyzed. The power required for various levels of self propulsion are reported.

Implications of the Ocean Drifter on global finfish production will be discussed as well as issues of liability and registration. The implications of various modes of operation will also be presented and the economic efficiency of operating in reciprocal or gyre currents explained. Strategies for their operation as manned or autonomous platforms will be discussed.

Background:

Increased demand for quality seafood together with reductions in commercial catch due to depleted stocks present unique opportunities for the growth of marine aquaculture.

As a result, the global production of aquaculture products has increased by 200% between 1985 and 1994 to a level of 18.5 million metric tons (MMT) worth $33.5 billion (1).

Two growth areas have emerged, offering even greater opportunities for seafood production and sustainable coastal economic development. These two areas are the land-based production of fish in recirculating systems and the culture of marine species in the open ocean.

Land-based recirculating aquaculture involves the use of tanks and water processing equipment to allow the culture of fish in a closed environment (2). Through a combination of filters, a bio-reaction unit for nitrifying ammonia, a sterilizer, and aeration, the same water can be used again and again. While it is possible to include a further treatment processes that totally eliminates the need for any water changes, a more common approach is to replace 5 to 10 percent of the water each day. Nitrates are thereby kept at a safe level, while water usage is such that controlled-temperature grow-out is feasible. In addition, water discharges are small enough that complete post treatment is achievable, allowing any discharge standard to be met.

The second emerging method of aquaculture is open-ocean fish farming. It differs from the conventional pen-raising of fish is several important ways. First, it is carried out in areas fully exposed to the ocean. The benefit of this high-energy environment is the rapid and effective dispersion of waste products produced by the fish, essentially eliminating the potential buildup of this material on the seabed beneath an installation. However, special measures are needed to ensure the survivability of the system and its product. Survivability can be achieved by size or robustness of the system, by submergence, or some combination.

Outwardly appearing as the opposite ends of the aquaculture spectrum, these two emerging methods are actually very related. They are both technology based approaches which depend on recent advances for commercial cost-effectiveness (3). In the U.S. these methods are being developed in response to the requirements of the Clean Water Act, legislation that restricts the discharge of pollutants into U.S. waters. It is logical that the growth of aquaculture would include both approaches depending on the species under cultivation. In addition, open-ocean operations would likely be dependent on shore-based, recirculating hatcheries to supply animals for on-growing.

The Impediments:

In the United States, an impediment to the growth of open-ocean fish farming is the array of regulatory requirements imposed on any proposed activities (4). A second impediment is the lack adequate legislation to cope with user-conflict issues and matters of the exclusive use public waters for private operations (5, 6).

It must also be pointed out that neither land-based recirculating systems nor open ocean systems are universally accepted as commercially mature technologies. In addition, the list marine species that can be considered fully commercialized is short, though progress is being made towards bringing additional species to commercial readiness.

To date nearly all applications of sea farming technology in the U.S. have been in sheltered-water locations. Aquaculture sites are typically established after a rigorous public review and permitting procedure. The finfish cages are typically rafts or circular plastic rings supporting netting enclosures whose shapes are maintained by weights along their lower perimeters. These cages or arrays of cages are held in place with elaborate anchoring systems.

The vast potential of the worlds oceans will remain untapped until finfish and shellfish grow-out systems are developed that reflect the harsh realities of full ocean exposure and are demonstrated to cost effective. The remainder of this paper describes an innovative approach that may revolutionize ocean-based fish farming.

Ocean Drifter:

In 1996, a novel offshore fish farming system was introduced (7). This patented technology (8) is called Sea Station™ and it is pictured in Figure 1. It is composed of a single vertical cylinder called the spar buoy. This central spar is surrounded by a large-diameter rigid ring. Running from the ring to the top and bottom ends of the spar are two cones of containment netting.

Figure 1. A drawing of Sea Station™ prototype I.

The advantages of Sea Station™ over conventional cages are numerous. Most important, however, is that the resulting volume of contained growing space is stable and does not collapse in a current as with most cages. In addition, the taut netting is important for durability and predator control. The design has been proven in several locations worldwide including Puget Sound, Long Island, N.Y., and the Philippines. To date, these cages range in volume from 1,000 to 3,000 cubic meters. They are designed to be anchored like conventional cages but they can be submerged in the event of extreme weather.

The Ocean Drifter is an extension of this proven technology. It is larger than Sea Station™ and intended to be operated without a designated site, continuously moving within large, predetermined area. The advantages of this approach is that by drifting over a large area, concern over negative impacts to the seabed is eliminated and the operation becomes ecologically sustainable. The approach would simplify the often costly and time consuming permitting process associated with obtaining the exclusive use of a site. The ability to move would allow the operation to avoid toxic algal blooms or other pollution threats. Ocean Drifter could respond to the seasonal changes in water temperature, optimizing fish growth and health by strategic positioning . Obviously some form of control must be exercised over an unmoored pen to prevent catastrophe. Through constant position monitoring and a means of self-propulsion, the Ocean Drifter could provide important advantages over conventional fish-farming methods.

Through a project funded by the Sea Grant Industrial Fellowship Program, research has been conducted, aimed at the development of this novel approach to open-ocean aquaculture. The project, is a collaboration between the MIT Sea Grant College Program and Ocean Spar® Technologies, LLC.

Along with the advantages cites above, the Ocean Drifter introduces new challenges. A continuously moving sea farm will need to operate in the larger sounds, seas, and oceans and will have to survive the severest marine weather conditions.

Our initial task was the characterization of Sea Station™ using model tests. Tests were accomplished in the summer of 1996 on a 4.5 scale model using the DTMB wave tank. In addition, OST personnel towed Sea Station™ Prototype I, a 2000 m3 cage, in Puget Sound, gathering additional resistance and operational data.

Based on these results, a propulsion/maneuvering system was devised. This system included two parallel propulsors on the submerged ring facing "aft" and one steering thruster facing "sideways". For the purposes of the model tests, the two primary propulsion units were thrusters from a Benthos MiniROVER Mk II remotely operated vehicle. The steering thruster was a smaller unit from a MiniROVER Mk I. These thrusters provided a convenient means of accomplishing the tests, though their design is not viewed as necessarily appropriate for this low-speed application.

We developed a preliminary Ocean Drifter design based on the geometry of the Sea Station™ model. The size of the system is aimed at equaling the largest of conventional sea cages currently in commercial production. Table 1 provides the basic prototype dimensions. The model dimensions follow in Table 2.

Ring diameter	270	ft	82.3	m
Height	174	ft	53	m
Normal draft	150	ft	45	m
Light draft	75	ft	23	m
Volume	1,572,750	ft^3	44,550	m^3
Displacement	313	LT	317	T

Table 1. Principal dimensions of the Ocean Drifter.

Scale	1/15			
Diameter	18	ft	4.9	m
Height	11.6	ft	3.5	m

Draft		10	ft	3.0	m
Volume		466	ft^3	13.2	m^3
Displacement:	ring	73	lbs	33	kg
	spar	135	lbs	61	kg
	total	208	lbs	94	kg

Table 2. Model Description

The Ocean Drifter model tests were also done in the DTMB wave basin. This 360' long by 240' wide by 20' deep facility is ideal for the evaluation of such systems. A test program was developed to address the factors we viewed as important to the further development of the Ocean Drifter concept. This test program is described in Tables 3 and 4. All tests were done both with and without the net deployed.

Calm water resistance
Bollard tests
Self propelled tests
Seakeeping in regular waves
Drifting in irregular waves

Table 3. Model testing program.

Data acquisition was through a hard-wire tether from the model to the wave basin carriage. The sensors were connected to a Computer Boards CIO-SSH16 simultaneous sample and hold/gain adjust interface. This fed a PC-mounted Computer Boards CIO-AD16Jr A-D conversion board. Data capture and presentation was accomplished using Snap Scope.

Parameter	Instrumentation
Heave	Z accelerometer
Surge	Y accelerometer
Sway	X accelerometer
Ring bending Mom.	Strain gages (x 13)
Resistance	500-lb submersible load cell
Bollard thrust	500-lb submersible load cell
Speed	Carriage display
Wave data	Manual input
Thruster watts	Manual input

Table 4. Model instrumentation.

Model Test Results

The results of the Ocean Drifter model tests are presented below in Figures 2-5. In these figures, data points are typically based on the average of 20 seconds of measurements, recorded at a sampling rate of 1000 Hz. The resistance and bollard pull load cell was calibrated manually over the full range of these test loads.

As is our usual practice for cage seakeeping tests, regular waves were used to determine the response of the system to various input frequencies. However, the unrestrained drifting tests were done using computer-generated wave spectra. For the self propelled tests, the carriage speed was carefully adjusted to match the speed of the model for each thruster setting and the velocity was recorded from the on-carriage display.

The lines connecting the data points in Figures 4 and 5 are simply interpolations and included for clarity, not meant as fitted curves.

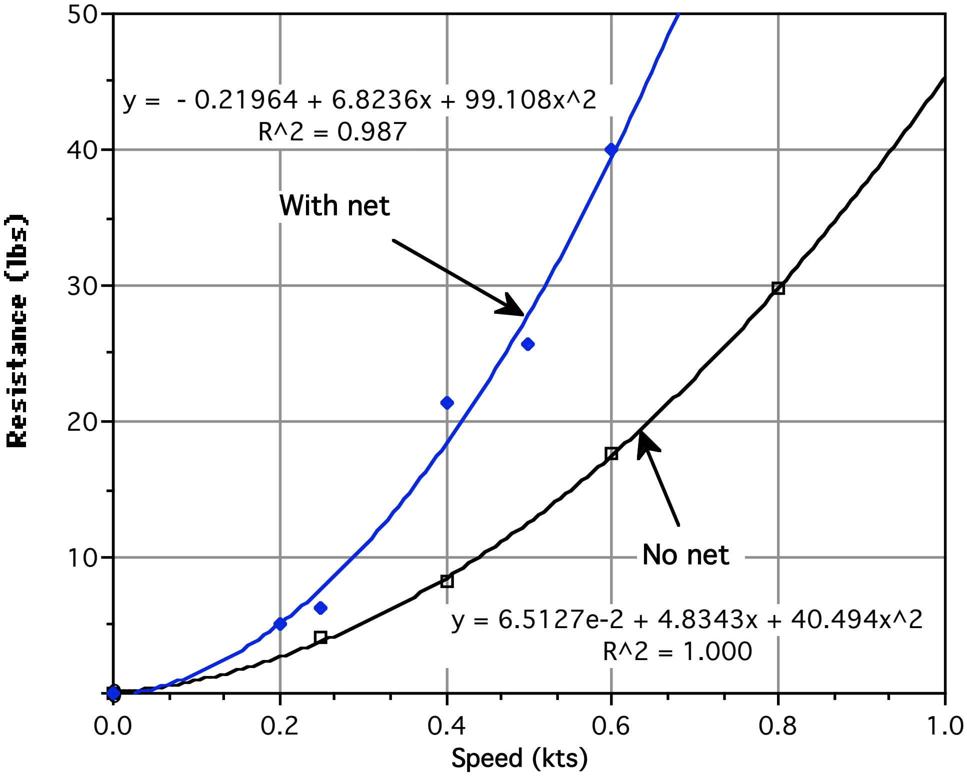

Figure 2. Resistance vs. Speed

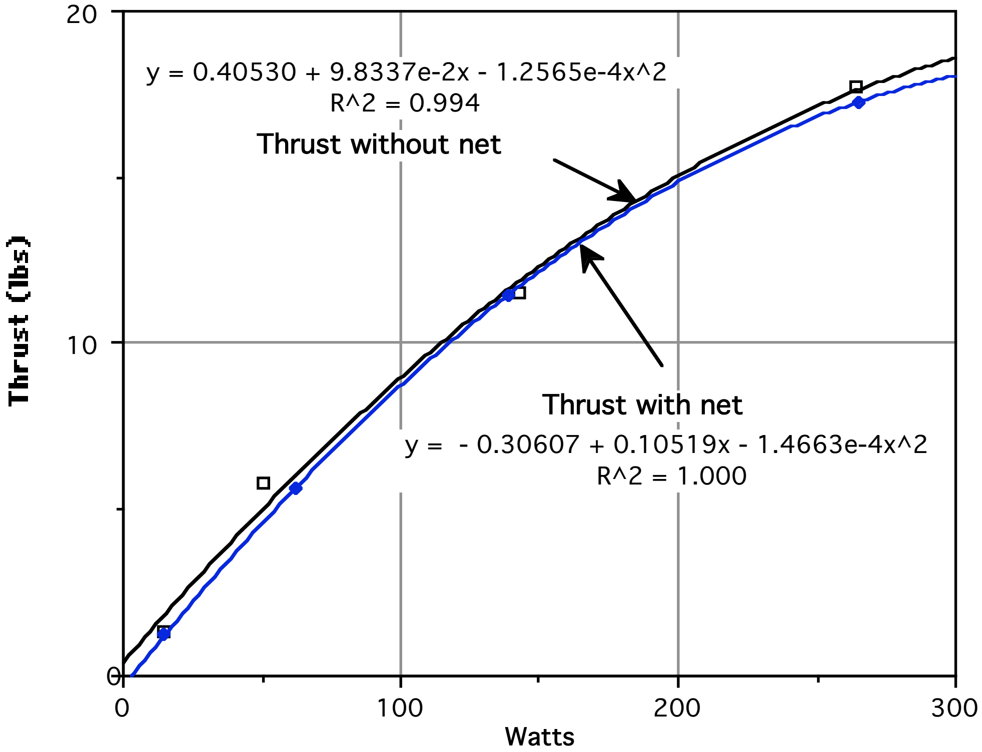

Figure 3. Bollard Tests

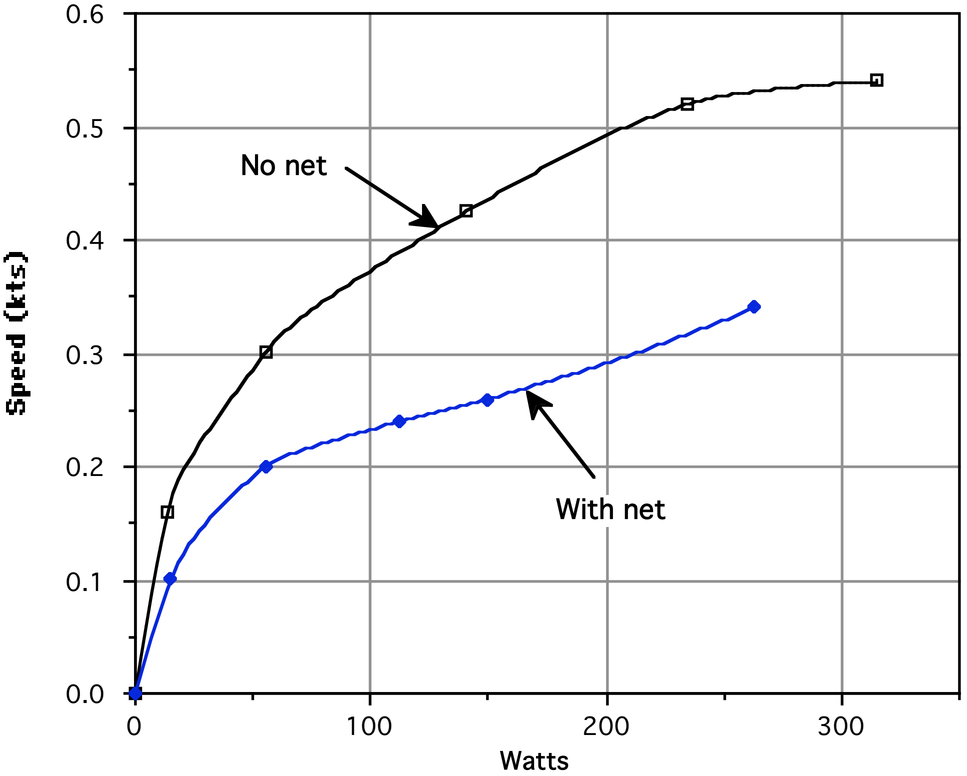

Figure 4. Speed vs. Power

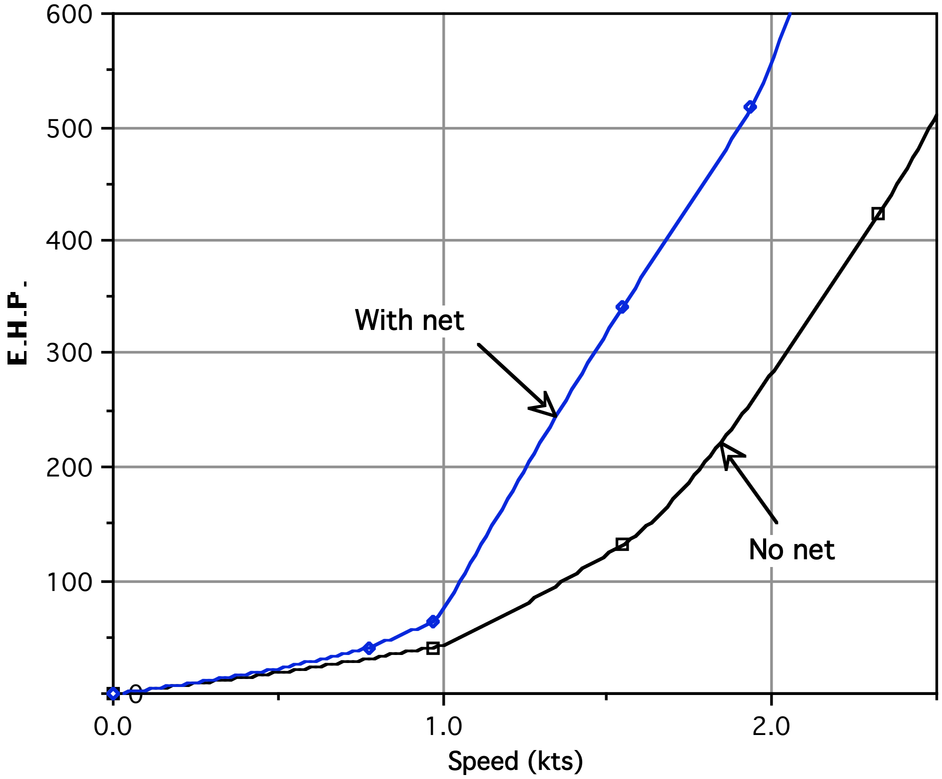

Figure 5. Predicted Full-scale E.H.P. vs. Speed

Discussion:

Figure 2 reveals that the containment net represents over half of the system resistance and therefore actual resistance will be a strong function of the netting used and level of bio-fouling. The predictions presented in Figure 5 were based on a simplified Froude-based scale up of the model results, ignoring the conventional ship model data reduction techniques which separate wave-making and frictional resistance components.

The similar results of the two bollard tests indicates that the net has only a minor influence on the zero-speed performance of the thrusters. In spite of the size and proximity of the net to the thruster intakes, the high porosity of the netting results in little change to the velocity field seen by the propulsor.

While the calculation is tempting, an extraction of an overall system efficiency is of little use. The performance requirements of the ROV propulsion units used in the model tests have no relation to those required for low-speed, high-drag cage propulsion. Optimal propulsors for Ocean Drifter would be larger in diameter for low-speed efficiency, with little regard for reverse performance.

Conclusions:

1. The ring-mounted propulsor arrangement provided effective propulsion with good maneuverability.
2. Propulsor performance is only slightly affected by the presence of the net.
3. Low-speed propulsion can be achieved with low power.
4. Maneuverability can be achieved without steering thruster.

5. The arrangement tested is tolerant of one thruster failure.

Future Plans:

We have several data-analysis tasks ahead of us prior to completion of this phase of our development. An analysis of the Ocean Drifter model seakeeping data is planned as those results will be useful in determining the conditions under which husbandry operations can occur.

We will identify a preliminary operating speed and develop an optimal propulsor arrangement using propeller prediction software. This propulsor design, combined with the effective horsepower (EHP) predictions will provide a sound estimate for our next project phase which is the modeling of Ocean Drifter performance in flow fields and realistic ocean circulation patterns.

As discussed earlier, the continuous movement of the fish farming operation is desirable from an environmental standpoint. However, given the substantial and predictable tidal driven currents in many of the world's oceans, this movement will not require continuous powered operation. Given the reciprocal or rotary nature of most tidal-driven currents, the propulsion system may see only occasional use for course corrections needed to counter-act wind-induced currents.

Since tidal currents are predictable and subject to computation locally, the Ocean Drifter position corrections could be made at very low speeds compared to the local speed of the entraining current. Such corrections would keep Ocean Drifter within a designated area. For operations such as servicing or harvesting, the Ocean Drifter could be vectored to a temporary shallow water anchorage.

Strategies for the efficient operation of Ocean Drifter will be developed which will strive for minimal energy use, the development of techniques for achieving navigational way points, and methods of risk reduction in the event of approaching storms. This project phase will conclude with a detailed design of a prototype Ocean Drifter sufficient for cost estimation. This design document would include all the Ocean Drifter sub-systems required for deployment as an operational fish production system, including fuel, feed, fresh water, accommodations, etc.

Based on the availability of funds, we will begin the prototype Ocean Drifter construction, deployment, and evaluation. Initial evaluation will involve engineering trials designed to measure the predictive capabilities of our modeling methods and obtain detailed data on component performance and reliability.

With the engineering trials complete, Ocean Drifter will begin operational trials with its first crop of fish. Understanding the behavior of fish in a captive environment is essential to good husbandry practices. Due to the sheer size of Ocean Drifter, unconventional methods for fish observation may be needed. Scuba diving is a common approach to this task on conventional floating pens. Through the inclusion of a submerged diver lock-out system, this practice could continue.

As a manned platform capable of self propulsion, Ocean Drifter would be governed by normal maritime laws. However, with the availability of command, communication, and control hardware, the autonomous operation of the system could be considered. Such unmanned operation would introduce a challenging area of regulation but the potential cost savings make its exploration attractive. We also plan to explore strategies for fleet operation where one service vessel would tend an array of Ocean Drifters, either manned or unmanned.

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