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An Overview of Fishing Vessel Energy Efficiency Work in Newfoundland and Labrador, Canada

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Abstract— **This paper gives an overview of the fishing vessel energy efficiency related work that has been done at the Ocean Engineering Research Centre (OERC), Faculty of Engineering and Applied Science of Memorial University of Newfoundland from the mid 1990s until the present. The areas dealt with are the energy efficiency effects of anti-roll technology in the form of passive free surface Anti-Roll-Tanks (ARTs), Bulbous Bow designs, the design and performance evaluation of a wave-piercing catamaran for fishing, the influence of vessel size and proportions, the design of fishing vessels for multi-species fishery, energy efficiency fact sheets for improving energy efficiency in the short term, and energy audit plus the collection of energy usage of seven boats representative of the “inshore” fishing fleet in Newfoundland and Labrador, Canada over a two year period.**

Keywords-Anti-Roll-Tanks; Bulbous Bows; Wave Piercing Catamaran; Vessel size and proportions; Multi-species fishing vessels; Energy Efficiency Fact Sheets; Energy Audit

I. INTRODUCTION

This paper deals with the fleet that is referred to as the inshore fleet, i.e. vessels that during most of this period were limited to being less than 19.812m (65ft) in length overall. These vessels were generally restricted to operating inside the twelve mile limit when the regulations limiting vessel length were first brought in. A large number of these vessels were limited to fishing a single species prior to the cod moratorium that was brought in 1992. After the moratorium most of the larger boats in the fleet were forced to fish significantly farther from shore and for fish multiple species. A significant number of the larger boats now fish 150 to 250 nautical miles from shore. Previously most of these boats fished inside the 12 mile limit. The fishing industry had to try to adjust to this new operating environment and the need to fish multiple species on a single keel. The OERC became involved in trying to help the industry find ways and means to work better in this new more severe environment. The change in operating environment and the need for fishing gear for multiple species, put pressures on the design of vessels to provide more fuel capacity, more deck, fish-hold and crew accommodation space. The existing vessels were modified to the extent that was possible and new wider and taller vessels were built. The latter resulted in boats that were significantly less energy efficient due to low length to beam ratios and resulting blunt bow angles. The length to beam ratios have gotten as low as 2 or slightly less in some extreme cases. Along with these proportions one also ended up with a significant amount of immersed transom. This caused these boats to pull a significant amount of water behind them with consequent increase in resistance. The unusual proportions have led to problems of extreme vessel motions and low overall propulsive efficiencies. The resulting roll motions would be extremely quick for vessels with little added top weight. Those that tried to add as much deck space, winches and fishing related equipment as possible would end up with at least one extra deck becoming excessively tall. The latter resulted in boats that satisfied the stability regulations but had both roll and pitch motions that are extremely slow and with very large angles of excursion. In other words they would end up behaving like vessels with inadequate stability. The reason for this is that the boat ended up with large roll and pitch inertias such that the inertia forces dominated the vessel motions. Clearly, the majority of the newer boats ended up with characteristics that were on the continuum between these two extremes, mostly with characteristics that were less severe than the two extremes. Steel boats that are wide and tall relative to their length would tend to have slower roll and pitch motions with larger amplitudes than fiberglass boats with similar proportions. This is due to the fact that the steel vessels have more mass located farther from the centre of gravity, thus increasing the roll and pitch inertias.

II. ANTI ROLL TANKS

The change in operating conditions significantly increased the need for stabilizing devices that would make it possible to fish in these harsher locations more distant from shore. The use of paravanes (see figure 1) was the dominant means used in the so called inshore fleet. Paravanes are designed to act like inverted lifting surfaces generating downward lifting forces when water flows over them, thereby reducing the roll motions. These are therefore most effective when the boat is steaming at full speed rather than at fishing speed and at zero forward speed. They also have the distinct disadvantages of increasing vessel resistance as well as being significant safety hazards.

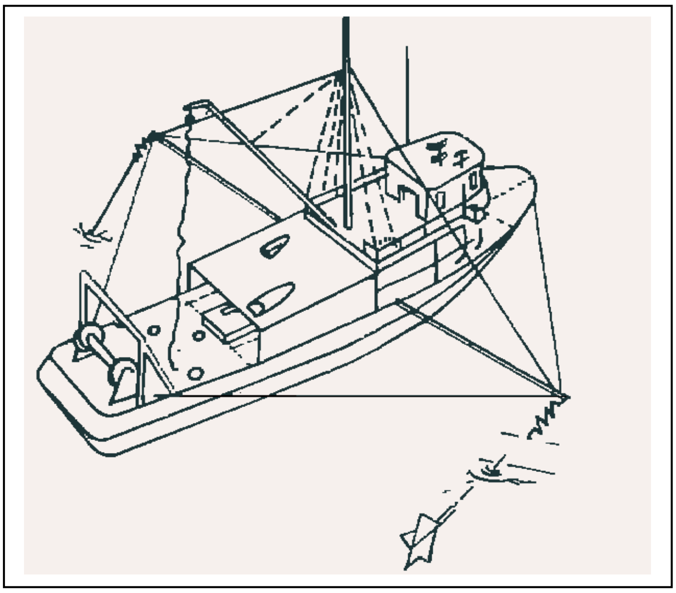

Figure 1: Fishing vessel with Paravanes deployed

This led to research into the use of passive anti-roll-tanks (ARTs). These work well in all normal operating conditions whether steaming or fishing. They are less effective in extreme conditions. *In such situations the roll excitation moment from the waves exceeds the potential restoring moment from the water in the tank. A tank is also less effective when steaming in stern seas when there is a very low encounter frequency and may amplify roll. The roll is generally quite slow and of small amplitude in these conditions.*

Prior to this, passive Anti-Roll-Tanks have been used on larger vessels but had not been employed on boats of this size category. This work led to the development of design tools enabling the design of the best possible tank geometry for a given vessel as well as using Computational Fluid Dynamics (CFD) modeling and simulation of the tank behavior.

In order to be able to fit a vessel with an ART it must first have sufficient stability to allow for the addition of the weight of the tank, its water as well as accounting for the additional free surface effect and still have satisfactory stability characteristics.

These free surface anti-roll tanks are designed to have their maximum efficiency in reducing vessel roll motion at the natural frequency of roll for the boat. They will ideally extend across the full beam of the boat and will contain an amount of water which corresponds to 1.5% to 3% of vessel displacement. The higher up in the vessel the tank is located the smaller the amount of water required. The geometry of the tank may also vary. The most commonly used is a rectangular prismatic shape with internal baffles fitted. These baffles may be vertical rods or a plate baffle as illustrated in figures 2 and 3. Another type of tank geometry is where a narrowing over a distance to either side of the vessel centre line occurs. This will result in some of the same effects as observed with the baffles. The purpose of the baffles is to moderate the flow of water towards the ends of tank such that saturation will not occur quite as readily as without the baffles. Tank saturation means that the water fully saturates the end of the tank as can be seen in figure 4. *When this happens the roll restoring moment due to the weight of the tank water will quickly level off with increasing roll.*

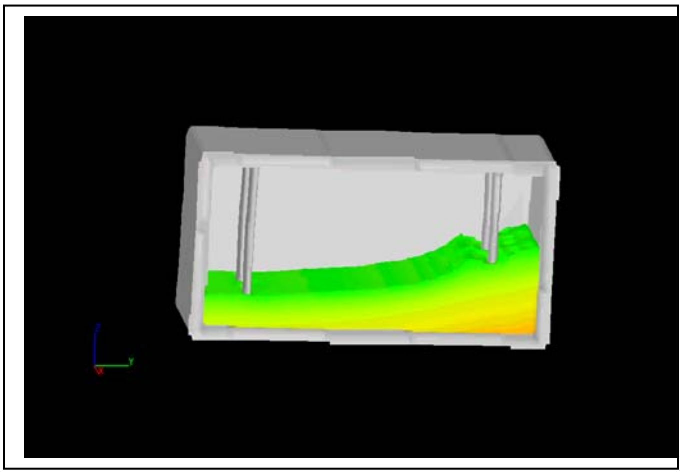

Figure 2: An ART with rod baffles

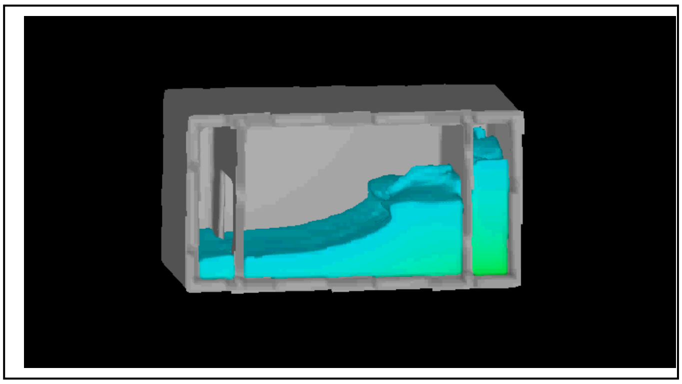

Figure 3: An ART with plate baffles

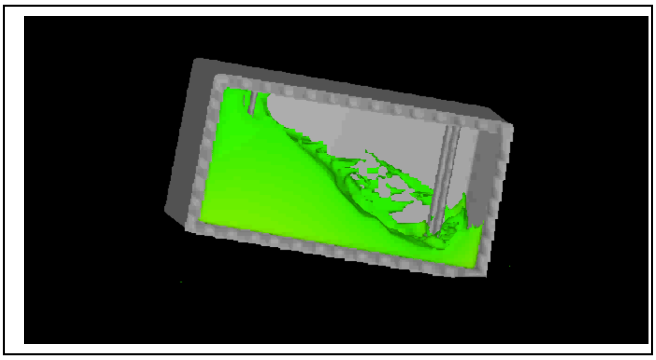

Figure 4: ART subjected to saturation

Clearly the tank has to be designed with a height that is such that premature saturation will not occur. Saturation will also reduce the righting moment that is created by the impact of the water on the tank end surfaces. The righting moment created by the tank is a combination of the moment due to the water weight transfer, the drag forces at the baffles and the dynamic energy of the water impact at the tank ends. These forces have to be phased relative to the vessel roll motion such that they give the best possible reduction in roll amplitude. In normal conditions, peak roll motion response will be at or close to the natural roll period, therefore the tank should have the same period of flow but with the desired phasing relative to the roll motion. *Optimally the restoring moment of the tank should be ¼ cycle out of phase with the roll motion.*

The water level in the tank will determine the natural frequency of the water flow. A low level of water will indicate a long natural period, while a higher water level will indicate a shorter natural period of flow as illustrated in figures 5 and 6.

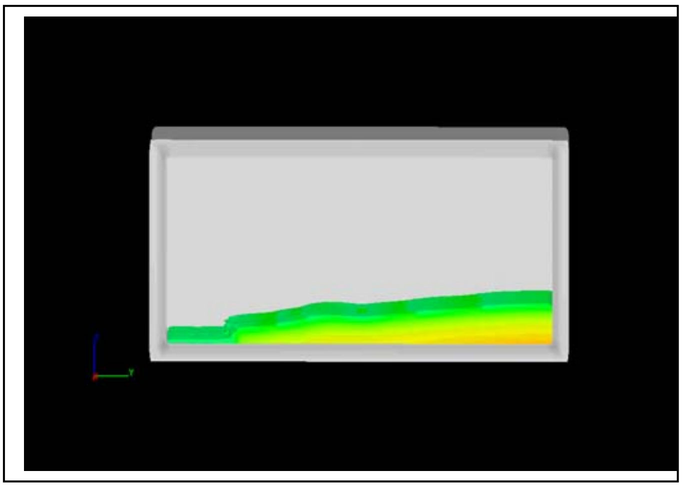

Figure 5: An ART with long natural period

The design tools developed makes it possible to quite accurately predict the water level in the tank that will give the desired natural period and phasing necessary to satisfactorily countering the vessel roll motions.

An ART can be tuned after installation by doing identically excited roll tests with differing water levels and measuring the resulting roll angle responses.

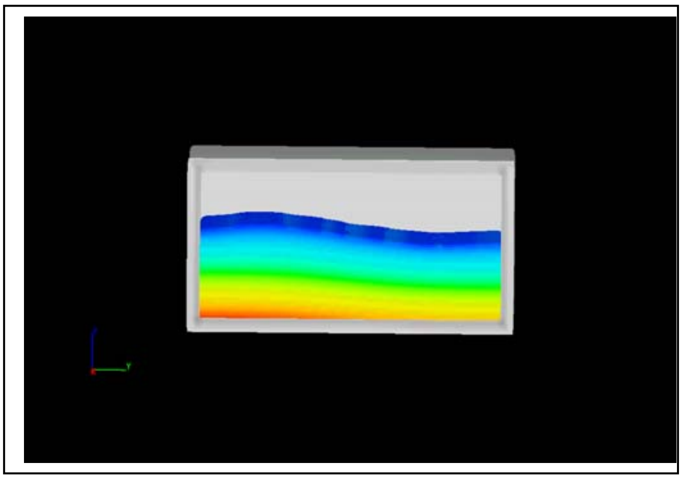

Figure 6: An ART with short natural period

The first tank installed on a Newfoundland and Labrador fishing vessel is shown in figure 7 [1, 2, 3]. There are now a significant number of fishing vessels that are operating successfully with ARTs in Newfoundland and Labrador as well as various other areas.

Figure 7: ART on F/V "Newfoundland Tradition"

The roll reduction that can be expected from a properly designed ART is generally 50% or better. In the most extreme case we have seen a reduction of as much as 75% has been observed. In contrast paravanes will give a reduction of 40 to 45% if the vessel has sufficient forward speed. One great advantage of a good ART is that it is just as effective without forward speed as it is while under way.

It should also be noted that paravanes have been found to increase vessel resistance by roughly 10%. An ART on the other hand will decrease energy consumption by creating a more stable work platform for carrying out fishing operations more safely, quickly and efficiently. Also the reduction in roll motion will reduce the vessel drag in a seaway while at the same time providing a more stable flow regime for the propeller relative to vessels with greater roll motions.

It should be noted that it is essential that the tank be designed by a qualified professional that is experienced in designing such tanks. An ART is a complicated dynamic device and it is easy for the tank to be ineffective or even detrimental if not designed properly.

III. BULBOUS BOWS

The next project studied the effects of retrofitting bulbous bows to a 19.8m (65ft) x 7.3m (24ft) fishing vessel (Figure 8). Two bulbs were studied. One was designed using the design principles outlined in Kracht's paper [4] and the other with a similar cross section at the front but significantly longer. The bulbs were also required to be able to operate in broken ice. This led to the bulbs being designed with a slope on its top surface as can be seen in Figures 9 and 10.

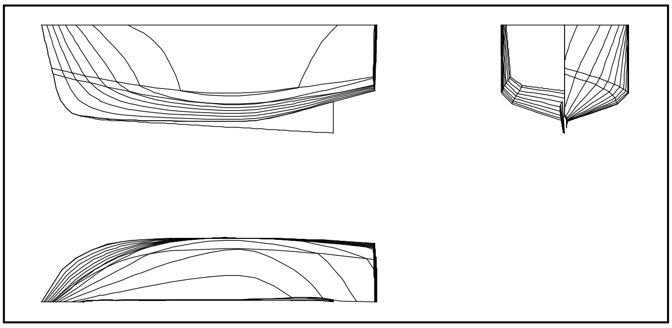

Figure 8: Original Vessel Lines

Note that the deck line shown on this and in figures 9 and 10 is below the sheer line of the actual vessel.

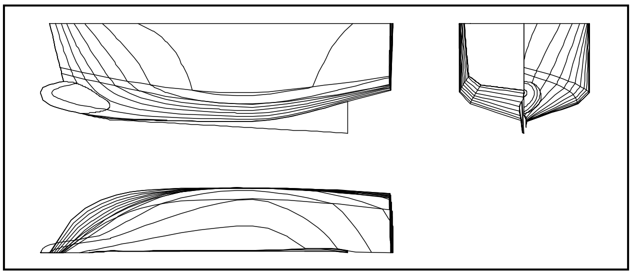

Figure 9: Hull with smaller bulb geometry

A model of this boat with three interchangeable bows was tank tested in the Ocean Engineering Research Centre (OERC) towing and wave tank. The results of this study showed that the percentage resistance reduction (Figure 11) from the two bulbous bows both peak at a vessel speed of about 8.5 knots. The reduction at this peak is of the order of 6% and 13% for the smaller (#1) and larger (#2) bulb respectively.

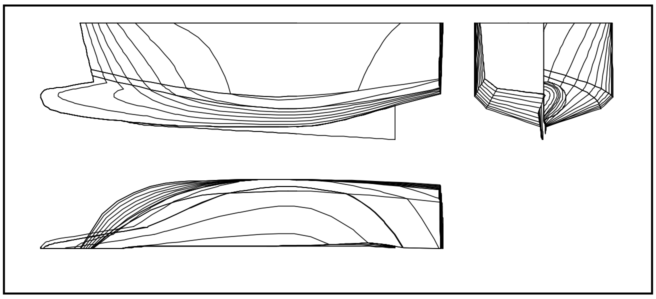

Figure 10: Hull with larger bulb geometry

The model was also tested in head seas using the JONSWAP wave spectrum with a model scale significant wave height of 73 mm corresponding to a full scale significant wave height of 0.96 m and a characteristic or average model scale period of 1.4 seconds. This spectrum corresponds approximately to that encountered on the Grand Banks of Newfoundland. Both the calm water and head seas tests were done over the entire vessel speed range up to a maximum corresponding to approximately 12 knots full scale.

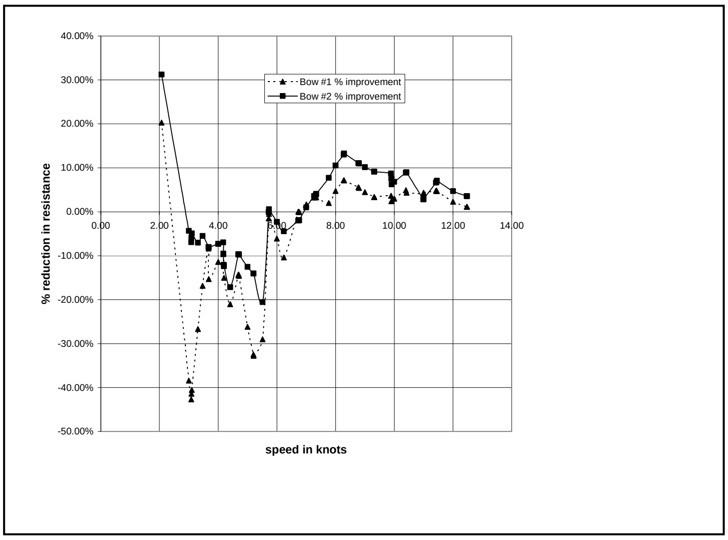

Figure 11: % change in resistance relative to conventional bow for the two bulbous bows

The relative performance in waves could only be measured with any degree of confidence at encounter frequencies close to those of a stationary model. However they did give a good qualitative measure of the relative resistance in waves. The main purpose of the head seas tests was to give an indication of changes in pitch and heave motion characteristics with the different hull configurations. Significant changes in ship motion and resistance characteristics were observed between the designs. Subsequent tests in regular waves with this model indicate that the results with the JONSWAP spectrum are indicative of the overall performance that can be expected in head seas at all forward speeds. The main conclusion from this was that there is good potential with a properly designed bulb to have a positive effect on the added resistance in waves. The longer bulb is clearly superior at the lower speeds up to around 7 knots full scale.

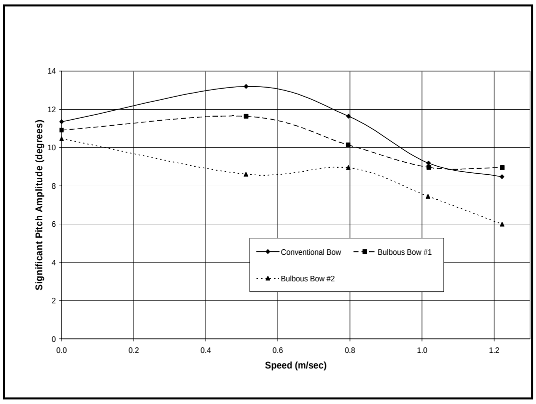

Figure 12: Model Pitch comparison for the 3 different bows

Even more significant is the reduction in pitch motion as shown in Figure 12 below. As can be seen the longer bulb performs significantly better over the full speed range. There were some differences in heave motion with again the longer bulb performing a slightly better than the other two bows over a significant portion of the vessel speed range. This initial study can be seen in more detail in reference [5].

This initial study gave us the reasoning and foundation to go forward with bulbous bow designs. The first boat to be fitted a bulbous bow was one of 15 sister vessels. These boats experienced significant trim by the head in almost all operating conditions. One operator attributed several near catastrophic instances of swamping to the trim by the head. Therefore, a primary design objective was to provide a significant amount of additional buoyancy forward. This was achieved by fairing the bulb waterlines into the boat's waterlines with straight lines. Further literature searches brought to light a study that had been done at MIT [6]. This paper used cylindrical bulbous bows and determined that the optimal bulb cross-section was likely to be of the order of 20% of the submerged midship section, and a length of about 1.5 times the bulb diameter. This gave us an indication of how much larger the bulb should have been relative to the larger bulb in our original study. Since a cylindrical bulb is likely to result in significant slamming motion it was decided to design a V-shape on the bottom of the bulb cross-section similar to the bulb in our initial study. The top part of the bulb had a circular cross-section with a diameter corresponding to 20% of the submerged midship section area. The bulb's top surface was also sloped upward in the profile view to allow operation in broken ice. Figure 13 shows the "Royal Mariner" that was the first of these vessels to be fitted with a bulb.

The owner-operator reported that after the first year of operation with the retrofitted bulb he had saved approximately 15% on the vessel's annual fuel bill as well as having been able to reduce the vessel operating time by approximately a month to catch his quotas. This was due to two things:

- Pitch motions being reduced such that he could execute various fisheries in much worse conditions than previously
- Being able to operate at 9 or 9.5 knots in conditions when he previously would have had to operate at 5 to 6 knots

Figure 13: F/V "Royal Mariner" after having bulbous bow fitted

Several of the sister vessels were also fitted with bulbs. Some of them had the same design as the "Royal Mariner", while others wanted a bulb that was easier and less expensive to retrofit. These latter bulbs were not faired into the waterlines, but maintained the same width all the way back while the bulb profile was maintained the same as that of the "Royal Mariner". The anecdotal information that came back from the users was that the semi-cylindrical design allowed the boat to achieve higher speeds than the bulb with faired in waterlines. The bulb faired into the boats waterlines with straight lines was reported to reduce pitch motions more than the straight semi-cylindrical bulb. Attempts were made to perform sea trials with boats before and after fitting a bulb, or with three vessels at the same time, one with the original standard bow, one with straight line fairing, and one with a semi-cylindrical bulb. Unfortunately, these trials were never conducted so the only information available on the performance of these bulbous bows is the anecdotal information stated above. Subsequent work done in the OERC tow tank has confirmed that these observations are correct. The semi-cylindrical bows tend to have better performance at Froude Numbers above 0.35 or so.

A number of other bulbs were designed and fitted on boats from 106.7m (55ft) to 30.5m (100ft) LOA. Figure 14 shows a 30.5m (100ft) boat under construction.

An extreme fishing vessel, the “Newfoundland Way”, was tested in the OERC wave-towing tank [7] with LOA of 19.8m (65ft), beam of 9.14m (30ft), and a depth of 9.14m (30ft). The distance from the bottom of the keel to the top of the wheelhouse was 16.5m (54ft). This vessel had extreme roll and pitch motions due to the fact that the roll and pitch inertias totally dominated the motions. The pitch motion was more akin to the way most other vessels roll. Our challenge was to try to modify the vessel by adding an Anti-Roll-Tank and a bulbous bow to see if we could obtain motions and resistance and propulsion characteristics that would be reasonable. The ART fitted was found to reduce the roll motion by about 75% in normal conditions as is illustrated in figure15. Several bulb sizes were designed and tested. The final bulb design managed to reduce the pitch motion by about 30% in head seas and head quartering seas and 20% in following seas and stern quartering seas. This still meant that the boat would be performing more poorly in following and stern quartering seas than other boats in the fleet. Since ARTs are not effective in extreme conditions this vessel could not have been considered to have roll motions that would be safe. The boat would then behave like vessel with inadequate stability due to the roll inertia dominating its motion.

Figure 14: 30.5m (100ft) vessel with bulbous bow under construction

The installed power required if the vessel is to operate at a cruising speed of 9 knots or so is 1000 HP or more. At a cruising speed of 10 knots it would require about 1500 HP installed. This is based on the assumption that a weather allowance of 25% is adequate. In all likelihood the vessel would experience a significantly greater added resistance in average wave conditions than this, so lower service speeds than 9 to 10 knots would be expected.

We did look at making modifications to the stern of the boat to reduce the submerged transom area. We managed to reduce this area by 50% which resulted in a reduction in resistance in calm water of 30%. This was done using CFD simulations that had been benchmarked against the model tests. This, however, is far from making this an energy efficient vessel.

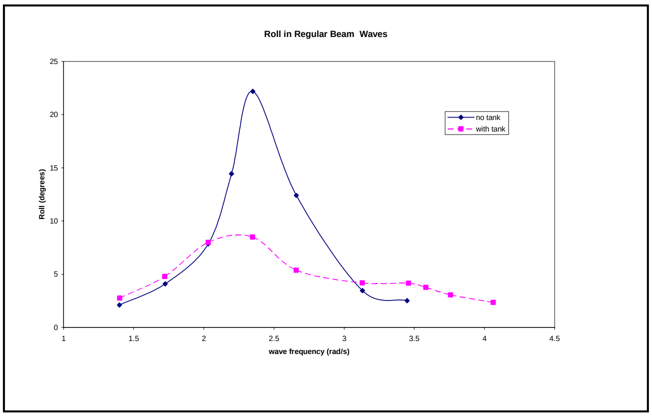

Figure 15: F/V "Newfoundland Way" roll motions with and without ART

The bow is very blunt. Due to the bluntness of the bow there is significant build up of water on the bulb at the higher speeds resulting in a dynamic trim by the head. In order to end up at a level trim at 9 knots or so the vessel needs to have a static trim by the stern of about 3 degrees. This is the situation with many of the newer vessels in the inshore fleet. Due to the length restriction they end up with a low length to beam ratio and a large angle of entrance. At the same time the 19.8m (65ft) boats have tended to be operated at 9 to 10 knots at which point the resistance curve is getting quite steep.

This is clearly far from being an energy efficient vessel. It requires 2.5 to 3 times the amount of power as the 19.8m (65ft) x 7.3m (24ft) that we did the initial set of tank tests on for bulbous bows. In addition to this it also would provide a less than stable work platform limiting the available time for executing the fishing operations etc. Unfortunately the proponent wanting to pursue this project did not take our advice not to go ahead with the project and proceeded to build it with some very minor modifications and renaming her “Arctic Leader”. She is shown in figure 16.

Figure 16: F/V "Arctic Leader

Due to the fact that Transport Canada is not considering her to be a safe vessel without significant lengthening she is now for sale by the bank that is the current owner of the vessel.

Further work on the energy efficiency of bulbous bows will be covered in the section on multi-species fishing vessels.

IV. WAVE-PIERCING CATAMARAN

We were approached by Bon Pelley Enterprises of Springdale, Newfoundland to tank test a wave-piercing catamaran hull intended for fishing. The hull needed to be checked out for resistance as well as seakeeping characteristics. The hull was tested for resistance with three different hull separations, 9.14m (30ft), 10.67m (35ft), and 12.2m (40ft). The boat's overall length was 65ft.

The demi-hulls as originally designed were fairly wide in order to give the desired displacement with a shallow draft. It quickly became clear that the relatively wide immersed transoms were a problem. The squat angle became quite large at a relatively low speed and just kept on increasing with no apparent sign of enough lift being produced as the speed approached the desired design speed of 20 knots or so. This made it clear that the hull form needed to be modified to get better performance. The hulls were stepped in a little above the intended design waterline and made deeper to maintain the same displacement capacity. The bottom of the aft end of the hulls was swept up at an angle of 5 to 6 degrees in order to significantly reduce the immersed transom areas. This worked, and resulted in a very significantly reduced drag and some lift at the stern at higher. This would allow it to operate at 20 knots or more in calm water and in moderate seas with an installed propulsion service power of 2000 HP, i.e. 1000 HP on each of the two shafts.

The investigation of hull separation indicated that there was no significant difference in performance for the three hull separations. The wider separation would increase hull weight and thereby negate any increase in performance. It was therefore decided that a 9.14m (30ft) overall vessel beam would be adequate particularly since this would enable the vessel to be taken out of the water by the Travelift at the local marine centre.

The seakeeping test program and associated simulations proved that both the initial and modified hull forms will perform better than or no worse than what is common for the Newfoundland 19.8m (65ft) fishing fleet.

It should be noted that to operate this type of vessel is quite different from operating a mono-hull. It is easy to get a GM that is excessive resulting in very quick roll motions. This in turn would limit the conditions in which it is possible to fish. Therefore, ballasting will be somewhat counter intuitive to somebody used to a mono-hull. In a lot of instances it may be necessary to add ballast high in the vessel to reduce GM sufficiently. Another thing is that the performance of this type of vessel is much more displacement sensitive than a mono-hull. Once the wider part of the demi-hulls is submerged the achievable vessel speed is reduced much more than a similar change in displacement in a mono-hull would result in. Clearly the achievable speed would still be much higher than for the corresponding mono-hull. At the heaviest displacement tested, but without the wider part of the demi-hulls submerged, on would expect to be able to maintain a speed of 15 knots. This is still significantly faster than the corresponding mono-hull. It was expected that the saving in fuel over the corresponding mono-hull might be of the order of 30% or better depending on operating regime and conditions.

The boat was built in aluminum and launched in 2004. Unfortunately she has not yet been operated for a full season of fishing due to various unfortunate circumstances. Consequently this concept has not yet been proven. The hull form is the property of Bon Pelley Enterprises in Springdale, Newfoundland and Labrador, Canada. A picture of the boat is shown in figure 17. More detailed information on this project can be found in references 8 and 9.

Figure 17: F/V "Atlanticat" after her launching in 2004

V. THE INFLUENCE OF VESSEL SIZE AND PROPORTIONS

During the fisheries renewal process that the governments of Canada and the Province of Newfoundland and Labrador were undertaking in 2006-2007 we were asked to look at the influence of vessel length on the ability operate the boat for a given set of operating requirements including a multi-species fishery and operating 150 to 250 miles offshore. This work built on some of the work done for the Multi-Species Fishing Vessel Projects covered in the next section.

This study examined 5 different boat lengths, 19.8m (65ft), 25.9m (85ft), 27.4m (90ft), 33.5m (110ft) and 45.7m (150ft) length overall. All the boats regardless of length had a 8.23m (27ft) beam except for the 45.7m (150ft) vessel which has the same length to beam ratio as the 33.5m (110ft) boat. In other words the L/B ratios were roughly 2.4, 3.1, 3.3, 4.0 and 4.0 respectively.

These boats were also to be engaged in fishing the same quotas except for the 45.7m (150ft) boat which needed a quota that was twice what the other boats were engaged in catching in order to be equally economically viable as the 33.5m (110ft) boat. It had a hold capacity of roughly twice the size.

It is well known that bigger fishing vessels can fish for a longer season than smaller vessels. Basically big boats are less 'lively' than small boats and if you can't stand up in a boat without holding on tight then it will severely limit your ability to carry on fishing. The key is to quantify what is meant by 'lively' and 'operability'. The liveliness of a boat can be assessed in terms of how many times you have to stop what you are doing and hold on.

The technical term for one of these events is a *Motion Induced Interrupt (MII)*. This is a criterion developed by the Navy (UK, US, Canadian?) that is based on the reaction of crew members to different combinations of heave, roll and pitch accelerations and amplitudes. The more MIIs per minute, the more likely the crew are at risk of injury and the more likely it is for fishing operations to be halted. In experimental assessments of the relationship of MII/minute to injury, 1.6 MII/minute is shown to result in a severe risk of injury.

A boat's liveliness increases with worsening weather conditions. If the waves are bigger, there are likely to be more MII per minute. The relationship of MII/minute for a particular boat to particular weather conditions can only be evaluated using computer simulations of the boat's motions in waves. The computer program (MOTSIM) used to evaluate motions has been extensively validated in model tests at National Research Council's Institute for Ocean Technology (IOT), Memorial University of Newfoundland (MUN) and Oceanic Consulting Corporation and in numerous sea trials of fishing vessels ranging in length from 35 feet to 75 feet.

In this study as well as other studies we have done, it has been shown that MII/minute decrease with increasing vessel length for given weather conditions. This relationship was further quantified in this study. Longer boats are more stable platforms to work on. Longer boats can therefore operate for longer seasons.

For a boat of a given length there is a critical wave height such that if that wave height is exceeded, the vessel will not be able to effectively operate. Because this wave height also depends on vessel speed, heading and the character of the waves (swells or wind seas), this critical wave height has to be evaluated on the basis of averaging over a number of different speeds, headings and wave fields. Moreover the averaging has to be applied over the length of a typical trip.

More precisely, for a boat of a *given length* class, there is a *critical wave height* such that if the *average wave height* taken over a typical trip length is above that critical value, then that trip would not be considered a successful trip i.e. for that trip the vessel is *effectively inoperable*.

Based on monthly wave statistics for the operating area, averaged over a ten year period, it was possible to estimate the number of possible successful trips per month that can be made for a particular vessel. In general this number will depend primarily on length of vessel and to a lesser extent on its particular design.

This methodology was applied in the first phase of the study discussed in the next section in which we derived the number of monthly 5 day trips that could be made in a year. This was compared to data compiled by the one of the major operators in this fleet and found to be in good agreement.

An average value for the MII/minute for the 65 foot boat in the study taken for 2 headings, 2 speeds, 6 wave conditions, and for 6 working positions on the decks of the boat was approximately 1 per minute, associated with a critical wave height of 3 m.

This value was taken as the threshold or benchmark for a number of other vessels of different lengths and a critical wave height determined based on computer simulations. These are shown in the table and graph below.

Table I: Critical Wave Heights with Vessel Length and Threshold Values

Vessel Length	Critical Wave Height	Threshold, MII/minute
19.8m (65ft)	3.0 m	0.955
25.9m (85ft)	3.75 m	1.06
27.4m (90ft)	4.0 m	0.992
33.5m (110ft)	4.25 m	0.856
45.7m (150ft)	5.0 m	1.08

Based on these critical wave heights and 10 year wave statistics it was shown that the number of 5 day trips that can be made per month for each of the above vessels is shown in the following graph.

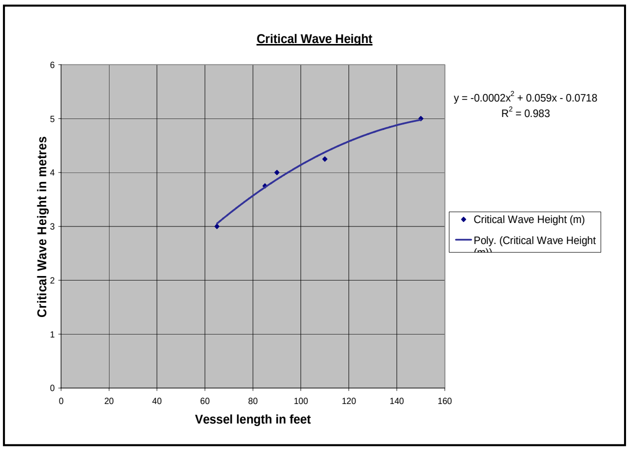

Figure 18 : Critical wave height for safe fish harvesting operations as a function of vessel length

The above figure clearly illustrates the claim about the relationship between vessel length and operability on a year round basis. This is directly linked to efficiency in executing the fishery and has a direct influence on energy efficiency.

To evaluate the relative energy efficiency the following assumptions were made:

- All the vessels being equipped with the same propulsion power plant
- This means that they will all be able to attain a speed of approximately 10 knots.
- All the vessels except the 45.7m (150ft) vessel are assumed to be operating with the same quotas.
- The quotas for the 45.7m (150ft) boat were approximately doubled as a reflection of the fact that its capacity is roughly twice that of the 33.5m (110ft) vessel. This also resulted in a rate of return of the same general order of magnitude as for the 33.5m (110ft) boat.

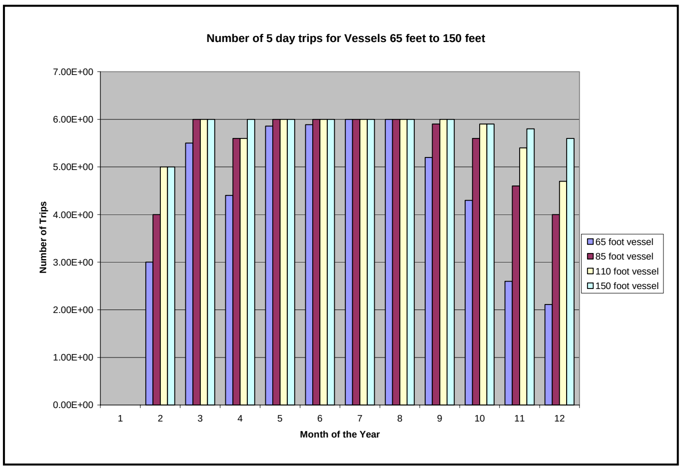

Figure 19: Number of 5 day fishing trips for vessels 19.8m (65ft) to 45.7m (150ft)

This study's energy efficiency Monte Carlo simulations gave us the following relative fuel consumption per lb or kg of catch is given in table 2 and figure 20. This is given in percentage of fuel used relative to the restricted vessel i.e. relative to the 65' boat we have:

Table II: Energy Efficiency as a function of vessel length relative to 19.8m (65ft) vessel

`	Relative rates of fuel usage per kg of catch			
	19.8m (65')	25.9m (85')	33.5m (110')	45.7m (150')
Average	100.00%	68.72%	59.56%	53.52%
Standard Deviation	100.00%	56.06%	84.54%	45.90%
+ 2 standard deviations	100.00%	66.50%	63.93%	52.19%
- 2 standard deviations	100.00%	72.13%	52.83%	55.58%

Based on some limited sensitivity analysis it is quite clear that energy efficiency is sensitive to the operating speed of the vessel going back and forth to the grounds. Operating all of these vessels at the same Froude Number it is clear that the relative energy efficiency would be much closer to equal for all vessel sizes. The 65' boat would still be less energy efficient than the others, but the other three would be roughly equal in efficiency. It follows that the vessels not restricted by the vessel size restrictions are superior in every respect including:

- Safety of vessel;
- Safety of crew;
- Fuel efficiency;
- Ability to carry on fishing operations in relatively adverse conditions;
- Consequent ability to catch full quotas of a wider variety of species;
- Ability to fish virtually year round thereby addressing many of the current industry issues related to seasonality of landings;
- Vastly improved handling and holding capabilities resulting in improved product quality;
- Better ability to retain crew due to a longer operating season & greater incomes;
- Overall ability to have an adequate return on investment.

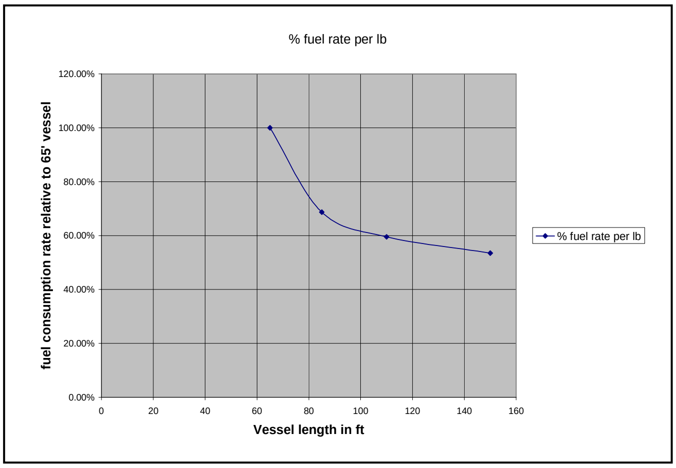

Figure 20: Energy Efficiency Relative to 19.8m (65ft) vessel

The safety of the vessel and crew has generally been taken to be satisfied through meeting the STAB4 vessel stability regulations. However, those regulations do not specify anything about the effects of vessel size relative to the wave environment in which these vessels are expected to be operating.

The 19.8m (64'-11") and smaller fleet of fishing vessels were quite adequately covered by these regulations when they were operating relatively close to shore so that they could get to port before conditions became severe. The changing nature of the fishery since the cod moratorium in 1992 has had a significant effect on vessel safety as well as the economic viability of this fleet. These effects include a requirement to go farther from shore to catch quotas such as shrimp and crab. This makes it extremely difficult to get to sheltered waters before the onset of severe storms. This in turn leads to increased likelihood of loss of vessel and crew.

The wind and wave environment in which they are operating is more adverse thereby shortening the available fishing time. This leads to an increased likelihood of crew injuries and loss of life. It is also the case that some of the older boats that predate the moratorium are at significant risk of running out of fuel before they can get back to port.

The move from operating a single to a multi-species fishery has led to new vessel designs that are wider and higher than fishing vessels of a similar length in other jurisdiction. This has resulted in vessels that in some extreme cases have motions that can only be controlled in normal operating conditions by fitting devices such as properly designed anti-roll tanks and bulbous bows, while rendering the vessel extremely difficult if not impossible to safely operate and control in extreme conditions. The increase in beam to length ratio has made these vessels even less directionally stable than they tend to be even at 20’ to 22’ beam. This has made these vessels more difficult to steer and has significantly increased the risk of capsize due to broaching in following and stern quartering seas.

From MII analysis the influence of vessel size on crew and vessel safety can be very clearly seen. A major contributing factor to the difference in motions and consequently the MIIs, is the vessel length relative to the predominant wave lengths. Another factor is the phasing of the vessel motions, in particular the pitch motion relative to the wave encounters. The unrestricted vessels are obviously performing in a superior manner on both these counts.

It is clear that the energy efficiency of the existing fleet is extremely poor simply because they spend so much time steaming to and from the grounds relative to the time they actually have available for fishing due to limited fuel carrying capacity. More details on this work can be found in reference [10].

Another study was undertaken for a 27.4m (90ft) boat design in which we varied vessel beam from 7.62m (25ft) to 12.192m (40ft). Powering was estimated using the Holtrop and Mennen method. This method gives reasonably accurate values for the narrower beams, but may underestimate somewhat for the larger beams. The hold volumes ranged from 224m^3 to 358 m^3.

Steaming at 10 knots the estimated fuel consumption rates ranged from 2918 to 5117 L/24-hours. This was then converted to dollars per m^3 per 24 hours and summarized relative to the 8.23m (27ft) beam as shown in table III.

Table III: Fuel cost per m3 hold space per 24 hours relative to 8.23m (27ft) beam

Beam	Difference Relative to 8.23m (27ft) beam in Fuel Cost $\$/\text{m}^3/24\text{hrs}$	Relative to 8.23m (27ft) Beam Fuel Cost/m^3
25	-$0.96	98.30%
27	$0.00	100.00%
28	$0.41	100.57%
29	$0.80	101.28%
30	$1.18	101.99%
32	$1.86	103.30%
34	$2.46	104.43%
36	$3.01	105.59%
38	$3.50	106.66%
40	$3.96	107.68%

The assumed fuel cost for the above estimates was $0.74 per Liter. This latter study was the initial part of phase 3 of the multi-species fishing vessel projects covered in the next section.

VI. MULTI-SPECIES FISHING VESSEL PROJECTS

This project was started prior to the fisheries renewal initiative and resulted in significant input into the process when it was started. It has been carried out in three phases. The first phase as described in references 11, and 12 involved designing two boats with the same mission, one was to be restricted by the maximum size allowed by the Department of fisheries and Oceans of the Government of Canada at the time. This was a maximum length of 64’-11” and a so called cubic number that was not to exceed 600 m^3. The other boat was to be free of any such restrictions.

The restricted boat ended up with a beam of8.23m (27ft) in order to comfortably accommodate twin trawl. The bow was designed with a smaller half angle of entrance than most of the newer boats in the fleet, but still a much larger angle than desirable at 51 degrees. The design displacement is about 218 metric tons.

Figure 21: Restricted Vessel

The initial design of the unrestricted vessel ended up with the same beam as the restricted in order to accommodate a twin trawl, but with an overall length of slightly more than 100ft at 30.79m. The half angle of entrance is in this case a more reasonable 35 degrees. The design displacement is about 396 tonnes.

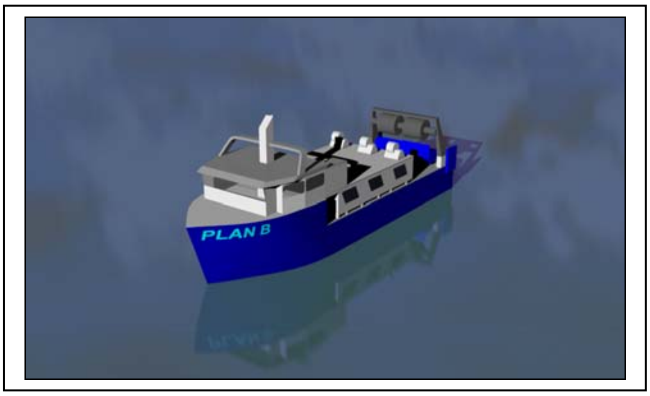

Figure 22: Unrestricted Vessel

A model of the restricted boat was built and tank tested for resistance since the vessel proportions are significantly outside the valid range for any available empirical formulae for estimating resistance and propulsion characteristics. It was found that the Holtrop and Mennen method did give resistance values fairly close to what was found from the tank testing.

Both vessels were designed to take a 636 kW engine which would enable both to maintain a speed of 10 knots. Clearly the restricted vessel would be slowed down significantly more in any significant sea state. This was confirmed by using CFD simulations to get another estimate of vessel resistance at a speed of 4 and 8 knots and calculating the added resistance in waves using the MOTSIM software package. This is shown in figures 23 and 24.

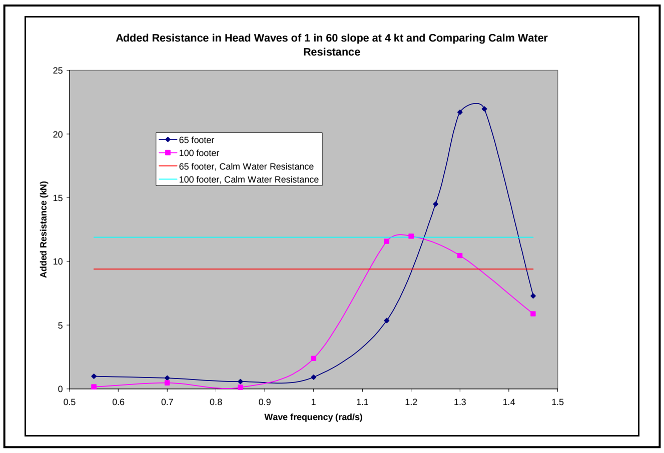

Figure 23: Added Resistance in head seas at 4 knots

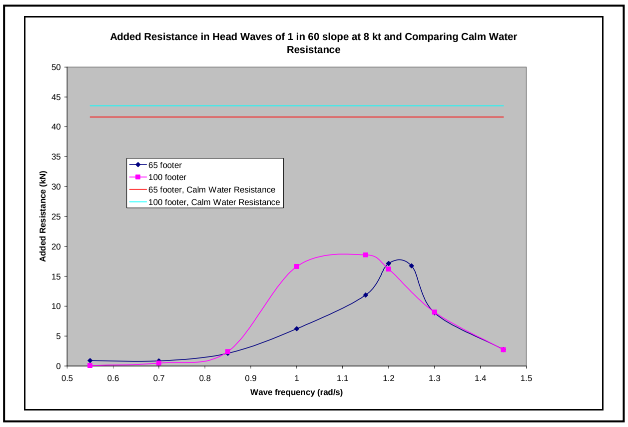

Figure 24: Added Resistance in head seas at 8 knots

There were also seakeeping simulations performed using the MOTSIM software. This package had been well benchmarked on similar vessels prior to this study. For the restricted vessel the limiting wave height for giving acceptable Motion Induced Interrupts (MIIs) would be around 3 m and for the unrestricted vessel around 4.5 m. This allowed the determination of the number of 5 day fishing trips per month based on wave statistics for a 10 year period for the relevant intended areas of operation as shown in figure 25.

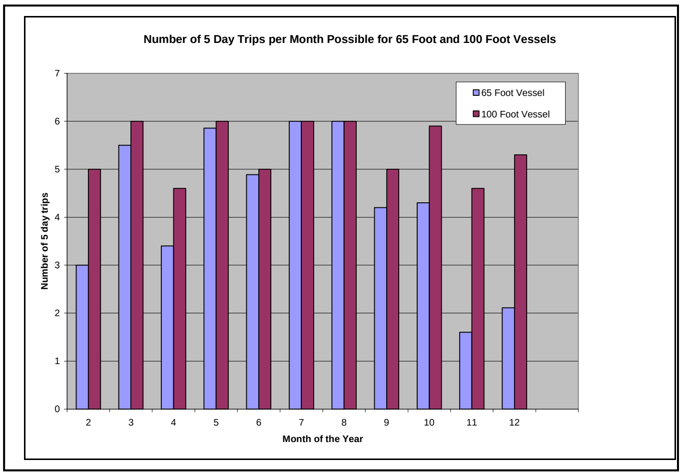

Figure 25: The number of 5 day fishing trips by month for the restricted and the unrestricted vessels

A full set of operational Monte Carlo simulations were performed to get a picture of the relative energy efficiency of these two alternatives plus the expected economic viability of the two vessels. This information was also used in the study discussed in the section on the influence of vessel length.

Before going on to Phase 2 of the project it was decided to modify the unrestricted vessel to achieve a more slender bow. This was done by stretching the bow out to an overall length of 33.73m or about 110 ft. This resulted in a half angle of entrance that had been reduced to 28 degrees or about a 20% decrease. Phase 2 consisted of resistance and propulsion testing of a 1.829m (6ft) model of this modified hull form [13]. In addition the self-propulsion testing was redone plus there were head seas tests performed measuring resistance plus pitch and heave motions [14]. The hull form with standard bow is shown in figure 26. The bulbous bows used in these tests are as shown in figures 27, 28, 29 and 30.

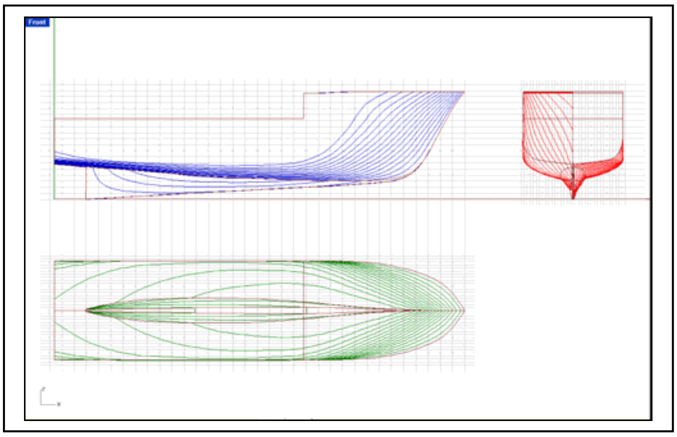

Figure 26: 33.5m (110ft) hull form with conventional bow

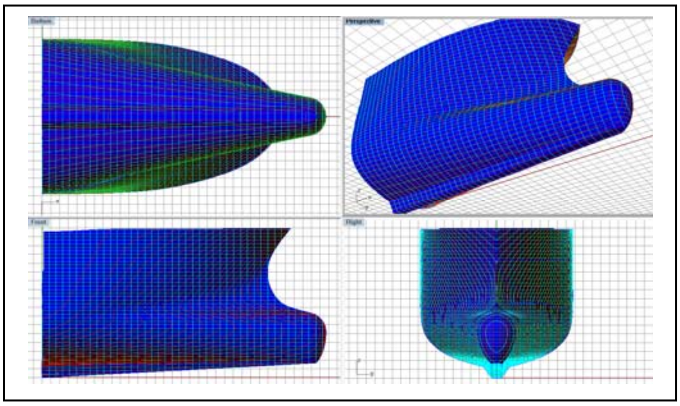

Figure 27: Bulb C faired into hull waterlines with straight lines

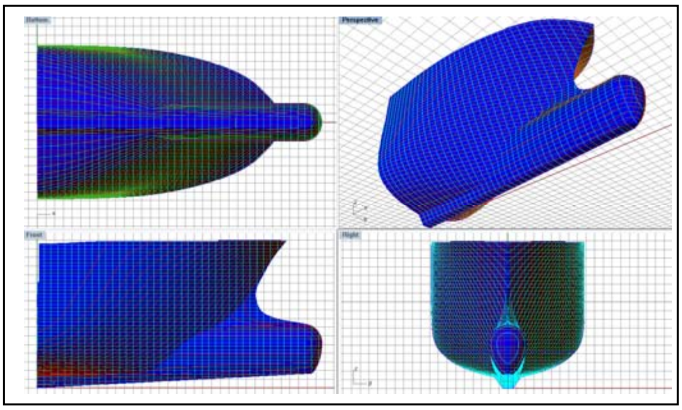

Figure 28: Bulb D the semi-cylindrical design, i.e. no fairing of bulb into hull

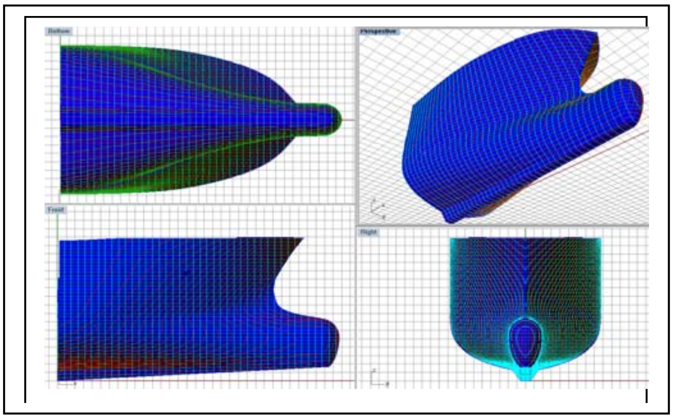

Figure 29: Bulb G with S-type fairing #1 of bulb waterlines into hull, i.e. with the smaller cross-section

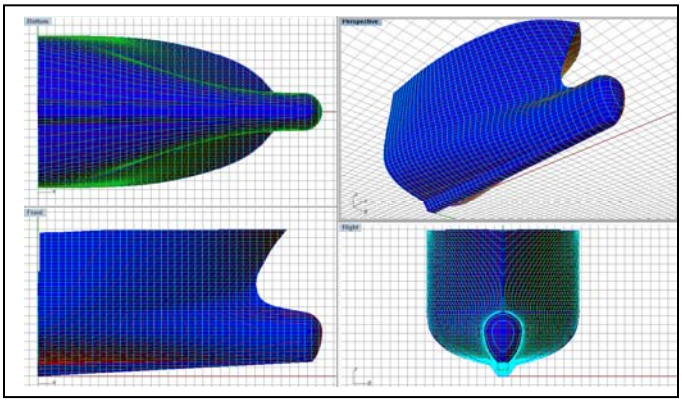

Figure 30: Bulb H with S-type Fairing #2, i.e. witrh the larger cross-section

The results of the resistance testing are shown in figures 31 and 32.

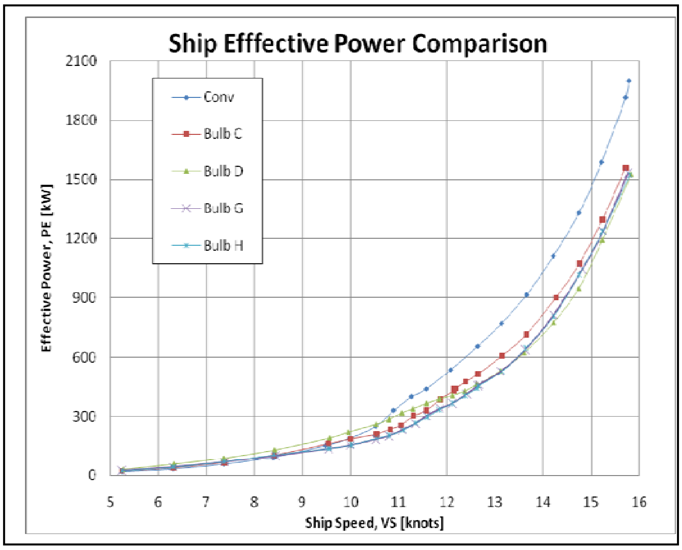

Figure 31: 33.5m (110ft) vessel calm water effective power comparison

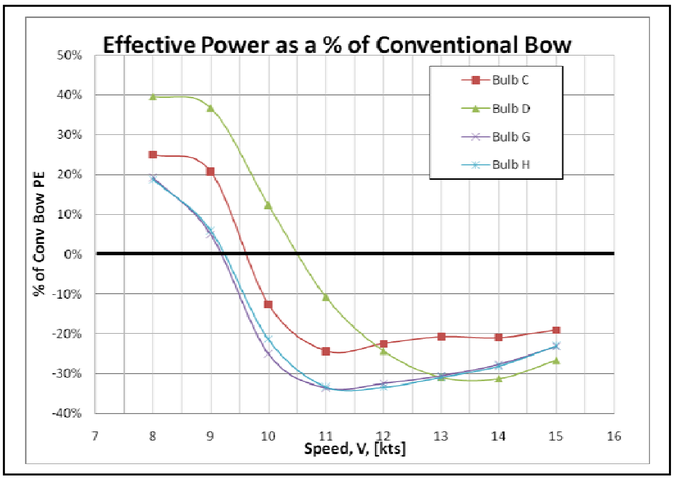

Figure 32: Effective Power as percentage of Conventional bow Effective Power

From a resistance point of view the bows with S-shaped fairing in of the bulb waterlines perform the best up to about 13 knots. At above 13 knots the bulb with no fairing in performs the best.

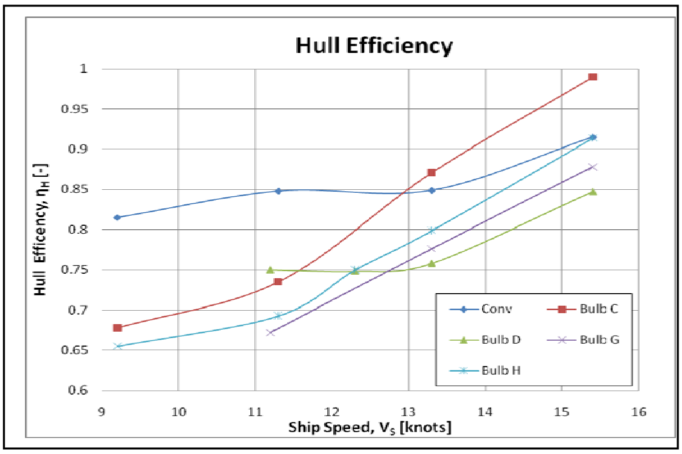

Figure 33: 33.5m (110ft) vessel hull efficiency for all bows

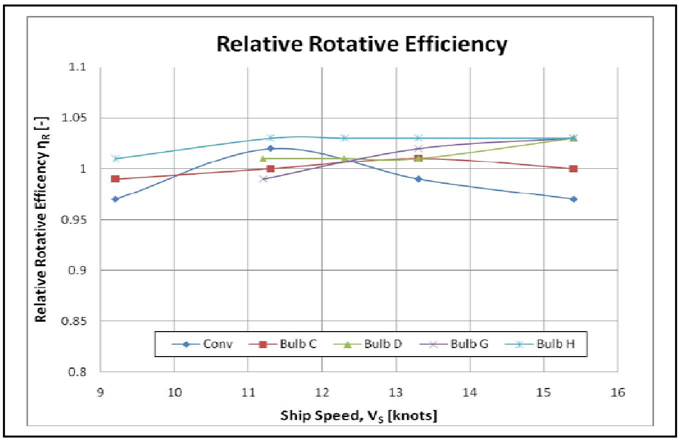

Figure 34: 33.5m (110ft) vessel Relative Rotative Efficiencies

The results of the self-propulsion experiments can be summarized in the form of the Hull and Relative Rotative Efficiencies. These are shown in figures 33 and 34. From these we see that the conventional bow gives the highest hull efficiencies below 13 knots. The bulb that is faired in with straight lines is performing the best above 13 knots and second best below 13 knots. The other bulbs are consistently performing worse over the full speed range. The Relative Rotative Efficiencies for bulb H is consistently best over the full range. The conventional bow is worst except over a range from 10 to 12.5 knots. The other bulbs are bunched in between the two. Designing controllable pitch propellers to suit the working conditions for these different hull configurations will result in open water efficiencies of about 0.55 or maybe slightly better or worse for all hull configurations over the range of speeds for which we have propulsion data. This results in the percentage savings over the conventional bow as shown in figure 35. We can see that bulbous bow H performs better than all the other bulbs over the full speed range except for over 14 knots. This is the bulb with S-type fairing of the bulb waterlines into the hull and with the bigger bulb cross-section.

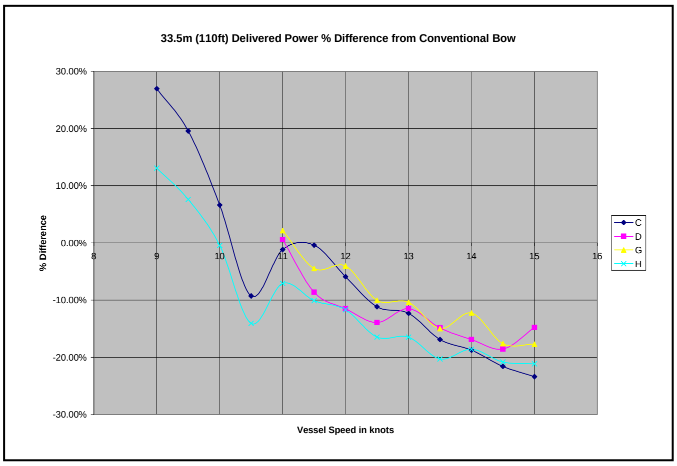

Figure 35: 33.5m (110ft) vessel bulbous bow delivered power as percentage of conventional bow delivered power

The head seas tests were performed with the model constrained in surge, roll and yaw. However, they did give a clear indication of the likely relative performance of the different bows. Bow C, the bow with the bulb waterlines faired into the hull with straight lines had the smallest accelerations in the direction of advance of the model indicating that this bow would be best able to maintain its speed, particularly in heavier seas. It also had the greatest reduction in pitch and heave motion relative to the conventional bow, particularly in heavier seas. Bulb C was also clearly getting the higher reductions in resistance relative to the conventional bow, particularly the heavier the sea conditions and the higher the speed.

Phase 3 of this project [15] was done after the changes to the vessel size restrictions were implemented and based on an overall length of 27.4m (89'-11") and 9.14m (30ft) beam. Resistance tests were performed with a conventional bow and three bulbous bows, one of each fairing type. From a resistance ranking point of view the S-shaped fairing performed best, with the straight line fairing being ranked second except at the top of the speed range where the bulb with no fairing performed better. However, it became clear early on that this hull suffered from some problems in the shoulder area such that a redesign would be beneficial. It also was decided that reducing the beam down to 8.23m (27ft) would not be detrimental from a hold capacity point of view. This effort is being continued in the current project.

VII. ENERGY EFFICIENCY FACT SHEETS

When the fuel prices went up rapidly it was clear that the industry needed some input into what they needed to do to reduce fuel costs. This resulted in a project that developed a set of fact sheets giving guidance on what steps can be taken now in order to reduce their energy consumption. A number of workshops were also conducted in different locations around the province during this process. The general approach was to take what we had developed as a preliminary set of approaches and recommendations to the workshops such that we could get feedback on the material as well as be made aware of other issues that we had not fully considered. This resulted in a final product that was significantly improved over our starting point. These fact sheets cover a range of issues from operational changes that may be taken to reduce fuel consumption like simply reducing vessel speed when going to and from the grounds. Installing fuel meters is one way that one can get direct feedback on the effects of reducing speed be certain amounts. We did a study for FPI a year or so before the company was broken up and sold in which we developed a spreadsheet model that could be used for optimizing the steaming speed [16]. Clearly, a fuel meter will allow one to home in on this point relatively quickly and easily. Other approaches ranged from machinery and hull maintenance issues through hull modifications like vessel lengthening and fitting of bulbous bow as well as the approach to take when wanting to invest in a new vessel. Fishing gear issues are also covered in one of the fact sheets as well as a sheet specifically aimed at small open boats. These fact sheets can be accessed on the Canadian Centre for Fisheries Innovation (CCFI) website www.ccfi.ca and follow the link "Fishing Vessel Energy Efficiency Workshops" and the Fact Sheets are at the bottom of that page. The complete address to this page is given as reference [17].

VIII. CONTINUING ENERGY EFFICIENCY AND AUDIT WORK

The latest project is one focused on what one can do to make the existing fleet more energy efficient. The approach is to try to map the energy consumption patterns of the fleet through collecting energy consumption data from a set of 7 boats. These are representative of the fleet both in boat size and in the types of fisheries that they engage in. The boats have been instrumented with fuel meters and weather stations including motion sensors. The data from this instrumentation will be collected and analyzed in conjunction with the vessel's log of fishing activities etc. Wave data from permanently installed Environment Canada wave buoys will also be correlated with this information. In addition sea trials will be conducted on each of these vessels with the shaft instrumented to measure the shaft power. A wave buoy will be deployed in the area of the trials to get more direct information on the wave conditions in addition to the other environmental data that is collected from the onboard weather station. A complete energy audit will also be conducted on each of the vessels through a thorough inspection of the hull and all machinery and other systems producing and consuming energy. This work will give the industry a picture of where energy is consumed and for what purpose as well as pointing out ways in which the hull and the various systems can be improved to save energy and by how much. The cost of possible improvements will be estimated and the payback periods and return on the investment calculated to make possible a rational business approach to improving energy efficiency. It is clear that this project will be likely to bring to light various operational practices that it would be beneficial to change in addition to those that have already been identified.

In addition to the above activities there will be model testing done on two models of fishing boats that are representative of a large number of the boats in the fleet. The fisheries renewal policies have been changed such that all the boats less than 19.787m (64'-11") will be allowed to be lengthened by 1.524m (5ft). This means that a boat with LOA of 10.643m (34'-11") can now be lengthened to 12.167m (39'-11"), a 13.691m (44'-11") boat to 15.215m (49'-11"), and 16.739m (54'-11") boat to 18.263m (59'-11"). It has been determined that the most likely approach to lengthening these boats will be by putting an extension on the stern with or without moving the rudder and propeller aft. Therefore these two models will be fitted with extensions corresponding to 5 ft for the models scaled to each of the length categories from 10643m (34'-11") through 16.739m (54'-11"). This will give us the ability to scale the models with their stern extensions to boats of the 19.787m (64'-11") category with extensions of different lengths. From some previous work done examining the effects of stern extensions on vessel directional stability and maneuvering capabilities [18] it is clear that in the majority of cases this group of stern extensions will cover the feasible range of such hull modifications.

A set of 3 bulbous bows, one of each of the three fairing types, linear, S-shape, and none, will be designed for each of the two hulls. These boats have half angles of entrance greater than 50 degrees so there may be a change in which fairing type works best from a resistance and propulsion point of view. It is likely that the linear type is still the best from seakeeping and head seas resistance points of view. There is also the intention is to investigate how the different geometric properties like the slope at the top the bulb profile and the fairing radius of the slope into the stem profile affect bulb performance.

This project extends over three years. The first year has been spent acquiring and installing the necessary instrumentation. The second year will give us a baseline set of data. After that season it is likely that some of the boats in the study will make hull and possibly other modifications. The third year will therefore provide data that will measure directly the effect of such modifications.

The 27.407m (89’-11”) boats are all likely to be built new, so some further work will likely be done to try to optimize hull forms for this size vessel for both fixed and mobile gear. Operators in the mobile fishery will generally want to be able to use a twin trawl which dictates a minimum vessel beam of 8.23m (27ft). For a fixed gear vessel there is no such restriction so one will be able to have a more slender boat. This size category is not the top priority for this project since it is likely only relevant to a very small number of operators at this time.

IX. CONTINUING ENERGY EFFICIENCY AND AUDIT WORK

Perhaps the most important thing to change in our current fleet is the hull proportions. We have some extreme examples of boats operating with length to beam ratios of around 2 or even slightly less. These boats end up having bows which are more like walls than an actual bow. These wide and blunt hull forms are clearly the greatest impediment to improving energy efficiency. In addition some of them have seakeeping characteristics that make them uncomfortable and/or less than safe.

The energy audit work and the data collected on energy consumption patterns in the fleet will form a basis for identifying the most cost effective ways in which the energy efficiency of the fleet may be improved.

The ongoing work on bulbous bows is likely to result in a clear set of design guidelines for matching hull form with bulbous bows and optimize performance for different operational requirements. The longer term goal is to develop simulation tools that will make it possible to accurately predict the seakeeping performance of hulls with different bulbous bow characteristics. The calm water resistance can already be predicted with reasonable accuracy using Computational Fluid Dynamics (CFD) software.

The larger long term challenge is to find ways in which to make machinery systems that are more energy efficient and not so dependent on fossil fuels as an energy source. Hybrid systems, fuel cells, wind power and solar energy are all avenues that need exploring and further development before any significant amount of practical application of these technologies is likely.

ACKNOWLEDGMENT

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