The Modern Superyacht ; Enlarged Yacht or Smaller Ship?

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Summary

The increasing size of the modern superyacht is pushing the boundaries of traditional yacht architecture. Large yachts are now more akin to small ships and the naval architecture, engineering and procurement of such vessels demands an increasingly rigorous approach. Coupled with ever increasing requirements for increased range, reduced noise levels and good seakeeping ability the engineering of these vessels requires a multi-disciplined approach with increasingly higher level technical input essential from the early conceptual design stage.

Within this paper the Author will examine a number of areas where mature technology developed within the commercial shipping industry is now being adopted in the yacht market and where some requirements specific to the large motor yachts are leading to adaptation of existing technology.

Introduction

Yacht design is often referred to as a careful blend of art and science. Historically the role of the yacht designer has encompassed both these disciplines with the successful designers of yesteryear possessing a good eye for style whilst integrating the latest technology through sound engineering skills.

Today the situation has changed somewhat with the role of the designer /stylist often separated from that of the naval architect. Projects generally begin life on the drawing board of the stylist and whilst he may have a good judgement for engineering aspects, the fact is that as yachts get larger and more technically complex there is an ever growing need for fundamental multi-disciplined engineering input from the earliest design stages. Whilst this separation of disciplines can often stimulate innovation with the creativity of the designer/stylist pushing the engineering boundaries, it also often leads to un-necessary compromise in some fundamental engineering aspects.

The size of the modern superyacht has grown rapidly in the last 10 years with vessels of 80m now being common place and yachts of up to 162m have been successfully constructed.

The technical demands required of these large motor yachts are generally encapsulated in the following fundamental requirements;

- Increased range capability and good seakeeping through close attention to optimisation of hull and propulsion system
- Stabilisation at rest
- Exceptionally low noise and vibration levels
- Good manoeuvrability and increasingly a requirement for DP capability

It is these fundamental requirements that are driving the leading naval architects and builders to adopt and adapt technology normally found in the commercial ship market.

Hullform Development

Examination of the trends in large (circa 80m) modern displacement motor yacht characteristics indicates that the majority operate with a length displacement of between 5 and 7 and a Froude number of up to 0.36. Given these two parameters the modern fleet shares some similar characteristics with the modern commercial ro-pax vessel.

These vessels mostly operate at a sub-hump Froude number of around 0.35. Hull forms are therefore more traditional displacement forms and the uniform operational profile results in most vessels utilising a bulbous bow. The current state the art hull-forms incorporate twin screws (either conventional props or podded drives) with wide-radius tunnels over the propellers and "gooseneck" type bulbous bows. Bulbous bow technology is largely mature yet a variety of different forms still prevail whilst differences in geometry are subtle.

Stern forms developed incorporate generally quite shallow buttock angles with wide and flatter stern sections. One form developed, termed a so-called "wave damping" afterbody, incorporates refinements of these features. The "wave damping" effect is reportedly achieved by careful hull form development featuring a long flat run aft, and a section shape which promotes buttock flow with optimised hull form coefficients and curve of sectional areas. Essentially this from is describing a properly optimised after body which results in a low wave making resistance component by limiting running trim without recourse to excessive trim wedges, whilst ensuring a good uniform flow into the propulsors.

Ducktails are also incorporated in many modern commercial forms. Typical improvements in resistance of over 5% are possible with the use of a ducktail. As Froude number increases the ducktails should ideally incorporate a slight trim wedge to control dynamic running trim. On yacht forms this is often observed as a discreet trim wedge but in the Authors experience it is better integrated as a return in the buttock lines. Return angles of not more than 2-3 degrees should be required to control running trim on a properly optimised form. Ducktails in effect offer an increase in length and many yachts essentially feature these as there is often a large, low freeboard bathing / boarding platform which serves the same purpose hydrodynamically as a ducktail as described.

Despite the requirement for increased range, a significant number of yachts do not utilise bulbous bows for practical reasons as they can cause problems when at anchor. Additionally given the operational profile of some yachts there may be little practical benefit from fitting a bulb with regard to overall fuel economy. At service speed however a bulb can offer a resistance reduction of up to 15% and should always be considered. Stern geometry is often constrained by the volumetric requirements of the large lazarette that feature on all yachts and often this results in a greater transom immersion and steeper buttock angles than are desirable hydrodynamically.

A specific example in the development of an 80m yacht is presented where a conventional yacht from, derived principally from smaller yachts and progressively scaled over a series of vessels of increasing size, was optimised utilising some of the aforementioned features. A parent form and resistance characteristics were provided to BMT Nigel Gee and Associates as a basis and the task set to conduct lines development and optimisation.

The initial optimisation process suggested by the yard involved testing a single model with multiple interchangeable bulbous bows including tests without a bulb. The Author does not however recommend this approach as the fitment of a bulb to a hullform demands refinement of the waterlines forward in close association with each bulb derivative. Additionally the bulb gives careful control over the LCB characteristics of a hullform and to remove an interchangeable bulb and replace with a non bulbous form leads to a non comparative analysis of LCB values and consequentially requires a different stern geometry to be used.

A revised optimisation process was proposed as follows;

- Optimise sectional area curve as far as possible within current state of the art practice
- Undertake comparative CFD studies on three different bulbous bow forms
- Perform model tests on the best form
- From model test observations and results refine lines further
- Test final form

The initial process involved optimisation of the sectional area curve and principal characteristics. From this a first iteration of the hull lines was derived (Iteration 1, Figure 1). These were largely derived from proven Ro-Pax and yacht forms within the main parameters of the parent hull. The lines incorporated the aforementioned gooseneck type bulbous bows featuring a slender neck and reverse form with the volume distribution concentrated near the DWL. The stern form adopted was partially based on the features previously described, however the constrains imposed by the requirement for a large and deep lazarette for tender stowage prohibited optimisation of the stern as much as would have been liked. A shallow trim wedge of 2 degrees was integrated by introduction of return in the buttocks.

From iteration 1 two further forms were developed; iteration 2 has the bulb volume raised somewhat so that the upper surface of the bulb is in contact with the DWL and the neck of the bulb has been narrowed slightly further. Iteration 3 has the bulb lengthened by around 1.5% LWL and a steeper return profile on the centerline buttock. It should be appreciated that these changes are only subtle, modification to the yachts bow profile was prohibited for styling reasons and this imposed subsequent limitations on the extent of geometric variations that could be explored. The principal characteristics of the variants and those of the parent from are presented in Figure 2.

CFD analysis was undertaken at three ship speeds, 12, 14 and 16 knots. The analysis consisted of inviscid free-surface calculations providing the wave pattern and wave resistance. The pressure distribution on the hull in the bulb/bow area at speed 14 kn are shown in Figure 3. The streamline originating at the bulb/stem intersection is also visualized in these figures.

Figure 4 illustrates that there are small differences in computed resistance between the three designs, however the bulb design of iteration 1 was slightly better than iteration 2 or 3. It was concluded that the knuckle line of iteration three was more optimum as it was better aligned with the local streamline.

Following the CFD analysis a final form, iteration 4 was developed based on a marriage of the iteration 1 and 3 forms. This was tested at Marintek in Norway. A comparison of the CR values across the speed range is presented in Figure 5. It can be seen that at a Froude number of 0.31 (relating to 16 knots) the achieved improvement in CR is in the region of 25% over the parent from. A further form was developed (iteration 5) as a result of testing which incorporated some stern modifications to reduce the trim wedge by straightening of the aft buttocks to almost completely remove the integrated stern wedge, leading to a further resistance reduction.

Whilst most significant yachts received this type of hullform optimisation process it is in many cases normal for this to be carried out fairly late in the design process (either post contract or very near to contract signature) with the result that the hydrodynamic package is often severely constrained by the arrangements agreed between the stylist and the owner. A better design process is to have the naval architect involved early in the design so that the hullform can be developed in parallel with the vessels arrangement and the right level of compromise achieved between the need to maximise interior volume and obtain a good hydrodynamic package.

Dynamic Positioning

Whilst the size of yachts grow, the size of the ports which they use remain largely static and become ever more crowded. This drives the need for improved manoeuvrability on larger yachts. Additionally many of these vessels now visit areas where anchoring may not be an ecologically sensitive activity.

These factors are leading to a number of yachts now requesting some form of dynamic positioning (DP) capability. The level of DP sought by modern yachts is (in most cases) not significant when compared with commercial vessels but the power requirements to achieve a reasonable level of capability can have a significant impact on the power demand. Hotel loads on modern yachts are relatively high with a typical 80m demanding around 600kW.

Figure 6 presents a plot of power required for DP vs vessel length. This is based on a simplified case for holding station in a beam wind of 15 knots for typical modern yacht windage profiles utilising thrusters. The power level required depends heavily on the type of thruster unit utilised. It can be seen that for an 80m vessel achieving station keeping in these conditions could double the hotel load.

Tunnel thrusters offer the greatest efficiency however these must be utilised in conjunction with the main propulsion system for DP capability as they have no azimuthing capability. Resiliently mounted units are now available with this development driven by the need for low noise and vibration levels. Retractable azimuthing units are occasionally used but as these can increase draught they are not generally favourable. Use of the main propulsion system in DP mode is preferably avoided as there is an associated increased in noise and vibration.

The use of pump jets is also becoming increasingly common. Whilst less efficient these units offer many benefits. Firstly, as they are mounted flush to the hull surface there is no additional appendage resistance. Secondly as they have full azimuthing capability they can offer DP capability without the need to run the main propulsion system. However these can be difficult to fit in the bow sections without imposing geometric constraint on the hullform.

The requirement for DP is one reason why a number of significant new builds have made the change to diesel electric propulsion systems.

Propulsion

The greater majority of the world's super yacht fleet are fitted with conventional propulsion systems comprising of CP or FP props driven by high or medium speed diesels. A very limited number employ a hybrid propulsion system comprising a gas turbine to provide a boost capability. However the demand for increased operational speed in the large yacht market is generally a niche requirement. Increased range and manoeuvrability are commonly of greater importance.

These two factors have led a number of recent new builds to specify diesel electric propulsion (DEP) systems coupled to podded electric drives. Three significant new builds between 65 and 90m launched in the last 2 years have seen this system utilised and they appear to offer solutions to many of the requirements discussed thus far.

Diesel electric systems are now fully mature technology and have been under continuous development since they were first introduced in the early 1900's (yes that long ago). Whilst a mature technology there is still a wide scope for refinement of DEP systems and advancements in computer control, switching technology and motor design are the key areas for advancement in a bid to reduce system losses and reduce weight. System losses are now as low as 8-10% between generator and propeller.

DEP systems afford greater flexibility in the positioning of the engine room and generally better utilisation of the onboard space. Additionally given the high hotel loads the ability to swing and manage power around the vessel is greater and more efficient. When used with a conventional prop arrangement they are certainly more space demanding and in all cases more expensive and complex. Recent reports however indicate that the cost issue is not as great as is widely believed with a diesel electric system reportedly adding approximately 1 - 2% on the build price when compared to a conventional system on a typical 80m yacht.

For vessels where there is a large variation in load demand, DEP systems can offer improved life cycle costs. With yachts now featuring DP in conjunction with high hotel loads the ability to manage this load variation is better achieved and improved life cycle costs can be achieved by reduced fuel consumption through optimised loading of generators.

To fully exploit the DEP concept the use of electric podded drives are now being utilised in large yachts. The podded, electric propulsor was first developed in the late 1980's and have since then matured to a proven product (not without some significant problems). Development has mainly taken place in the cruise ship market and the units have proven to be of major importance as a means to reduce cavitation, noise and vibration. In the case of the yacht these are critical factors and when married with the requirements for DP capability and increased manoeuvrability the podded drive appears an ideal choice.

The use of pods removes the associated appendage drag from shafts, brackets, rudders and stern thrusters. With appendage drag contributing to perhaps a much as 15% on large yachts (with the inclusion of anti roll fins and bilge keels) podded propulsors can lead to an overall power saving. The podded configuration utilises pulling propellers which allow good uniformity of the ship wave velocities resulting in extremely good cavitation characteristics of the propellers and reduce significantly propeller induced vibration and noise. Additionally given that the electric motor is mounted outside of the hull shell envelope the increased space associated with diesel electric systems is regained and generators can now be mounted on flexible rafts to reduce structural borne vibration. Recently a leading cruise operator has reported that the use of podded drives has, when carefully monitored over a seven day period, resulted in a 7% fuel saving, and when monitored purely in an at sea period (i.e. at service speed) the saving was around 10%.

Coupled with the flexibility in location of thruster devices and main propulsors that diesel electric affords, there is greater freedom in the hydrodynamic design of the hull form. The flat aft forms previously discussed are generally favourable from a resistance point of view and create a very uniform flow into the pod. However care should obviously be taken with regard to stern slamming.

Amongst this seemingly endless list of benefits, improved crash stopping characteristics can also be added to the list with crash stop distances of around 1.5 ship lengths being achievable from full speed. Reduced installation times are also claimed for podded drives with one recent 80m new build claiming that the use of pods cut up to 20 weeks of the build programme. The cost increase for a full DEP system coupled with podded drives is also claimed to be less expensive than might be anticipated with a recently reported cost increase of around 5% on the build price.

Hybrid systems are now being explored in the commercial market and CODED (combined diesel electric and diesel mechanical) are now in service linked to contra-rotating podded systems. In this case a conventional mechanically driven propeller is placed in front of an electrically driven pod, contra rotating to the main propeller. Efficiency gains of up to 15% are claimed and the pioneering customer of the arrangement has claimed an operational fuel saving of 20%. A number of very large yachts are currently under construction which utilise podded drives in combination with conventional propellers to offer a hybrid solution to more closely meet the specific needs of the yacht.

All of these apparent benefits do however come at the cost of increased complexity requiring a higher level of on-board skills to maintain and operate the systems. The high profile press coverage of pod failures in the cruise ship industry have served to leave many sceptical as to the reliability of this technology. These failures related mainly to bearings and seals and these appear to now be largely resolved. Commercial operator opinion is that the smaller units, typically below 14MW, are now problem free.

It is unlikely that the large yacht market is going to move wholesale to the use of either DEP or / and podded drives but the benchmark projects have now been launched which will surely lead to a steady move towards increased confidence in their use.

Stabilisation At Rest

Stabilisation of modern yachts is one area where technology derived from the commercial shipping sector has been adapted to meet the specific needs of yachts. An ever increasing number of manufacturers are now developing and selling at rest stabilisation systems and it is now more uncommon to hear of new builds which *don't* have a system fitted.

Modern motor yachts tend to be driven to higher GM values than is necessarily desirable. The deadweight faction of these vessels is typically quite low at around 15% -20% with the fuel load typically constituting 60 – 80% of the deadweight. The result of this is that the large consumable load, located low in the vessel, results in light arrival conditions becoming challenging with regard to stability criteria. Consequentially the GM values which the designer has within his control are often more limited than he may like. Natural roll periods tend to vary between 8 and 15 seconds and consequently motions in longer swells where the period is typically 7 – 14 seconds increases the probability of synchronous roll.

Given the operational profile of a typical yacht will be to spend a significant portion of time at anchor, the requirement for stabilisation systems that work when at rest has resulted and a wide range of solutions are being developed.

A number of equipment suppliers have developed fin stabilisers which require no forward motion to generate sufficient damping forces. Essentially a development of the conventional roll fin these systems use fins of increased area in a paddle fashion to create roll moments under at rest conditions. In order to create large enough forces at rest the fins require typically 30-40% more area than conventional roll fins and consequently a lower aspect ratio than is normal on conventional fins. Model test data indicates that reductions in significant roll amplitude in beam seas of up to 90% can be achieved (depending on the GM and natural roll period characteristics of the yacht). The operational feedback from yacht owners, and as reported in various public domain technical publications, is that these systems work well. These are now a mature and well proven product having been first utilised in 1999.

However as yachts get larger practical limitations are beginning to appear which is driving the need for new solutions. The fitment of anti roll fins is wholly scaleable with regard to vessel size but as length grows so too does the required size of the fins. Coupled with forms become fuller and speed increasing due to increased length so the use of fins becomes impractical. It is becoming increasingly difficult to fit the required fin area within the beam / keel envelope of the hull forms and the appendage drag increases to unfavourable levels.

A typical 80m will require approximately 25 sq.m of fin area whilst a 120m might require approximately 50 sq.m fin area. It is quickly realised whilst this technology is scaleable it becomes impractical much beyond this size of vessel. Where the exact limit is can be somewhat of a grey area as the fin area requirement for each project will depend heavily on the GM and natural roll period characteristics of the yacht, but it can be surmised that it is in the region of 120m.

Manufacturers of fin based zero speed systems are now exploring further developments and partially retractable and variable geometry fin area systems are just becoming available. The latter system offers a true dual purpose capability with relatively small fins utilised for the underway condition which employ a variable geometry system to increase the fin area for the at rest condition. It is reported by the systems manufacturer (Quantum) that a 30 – 35% increase in the fin size can result is as much as doubling of the roll damping capabilities. The first of these systems are due to be trialed in service in early 2007.

Fin based systems require about twice the power consumption of conventional fins and the installation cost is typically reported to be approximately 30-50% higher than conventional stabilisers. In practice these drawbacks are however far outweighed by the benefits and this is fully borne out by the number of owners specifying their use.

Fin based systems are not the only solutions available. Anti-roll tanks have been utilised in the past on yachts and these systems are well understood from application in the commercial field. The passive tank is designed such that roll moments from the tank are out of phase with the wave induced roll moments such that the ship roll motions are reduced. An active roll tank essentially performs the same task however being active the system is effective over a larger range of wave periods. Active and passive roll tanks work underway and at zero ship speed. These systems take up more internal volume and are therefore perhaps less suitable for yachts much below 80m where space is at a premium.

Anti-roll gyroscopes are also under development for yacht applications and are currently offered by one leading yacht manufacturer as standard on vessels up to approximately 30m. These were first explored in marine applications in the 1930's on various vessel types with varying degrees of success. Anti roll gyros make a compelling case for application as they can be easily installed and offer no appendage drag. However the major drawback with the current state of the technology is the size, weight and power requirements for these systems. Further development is currently being undertaken and one manufacturer reports to have a product range now available for yachts up to 100m.

Perhaps one of the most interesting products to come to the market recently is that of the rotary fin stabiliser. These utilise slewing rotating cylinders, deployed in a similar manner to retractable stabilisers, to create lift by the MAGNUS effect. Model test results with these systems on large yachts (over 120m) indicate that a reduction in significant roll angle of well over 80% can be achieved at zero speed. In practice it is believed that the largest vessel fitted with such a system is currently approximately 40m although it is known that systems are currently being supplied for yachts of over 150m for new build and retro fit applications. Whilst these systems are likely to be more complex mechanically they offer a practical alternative for larger vessels where as discussed, fitment of fins can become impractical.

A qualitative summary of the technical aspects surrounding the various systems described is presented in Figure 7, together with quantitative model test data (courtesy of Quantum) for zero speed fins, rotary fin stabilisers and variable geometry fins.

There are in summary an ever increasing number of options available to the modern yacht for at rest stabilisation. Suppliers are innovating new products to meet the challenges posed by ever increasing vessel size. Combining devices to achieve an acceptable level of motion both at rest and whilst underway may also become common place in the future.

Conclusions

As the size of the modern motor yacht continues to grow there is an ever increasing demand to employ technology developed in the commercial shipping industry. This transfer of technology is serving the technical requirements of the modern yacht. Additionally system suppliers are adapting existing technology to meet demands specific to modern yachts. Hullfrom development, dynamic positioning, propulsion and stabilisation at rest have been discussed, but the list is more extensive and topics such as the modern regulatory framework, safety aspects and lifesaving are other areas where large yachts are pushing the boundaries of previously established practices.

The increase in vessel size coupled with the adoption of this technology demands a higher level of technical input at the early design stages, especially with an increasing trend for the styling and engineering aspects of modern motor yachts to be distinctly separated disciplines. Whilst the wishes of the designer and stylist are often conflicting with those of the engineer, an early design stage collaboration and careful integration of technology and style will lead to yachts that, whilst looking ground breaking will also incorporate the right level of engineering optimisation to ensure that they do justice to the adage that yacht design is both art and science.

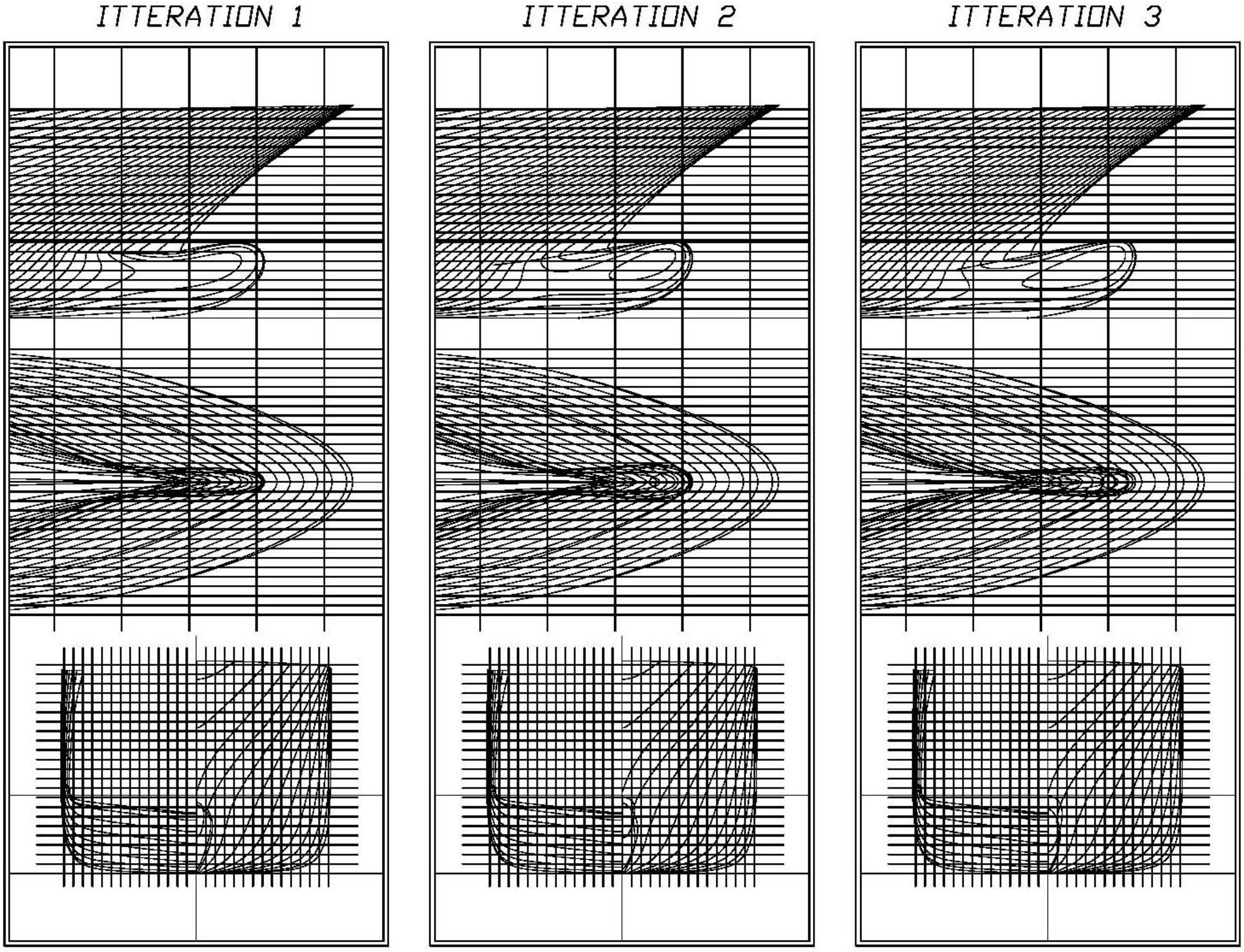

Figure 1 – Comparison of Forms Developed

	Parent Form	Iteration 1	Iteration 2	Iteration 3
Cp	0.626	0.593	0.597	0.596
CB	0.510	0.507	0.551	0.550
CM	0.836	0.855	0.923	0.923
LCB [% aft]	-2.676	-0.805	-0.871	-0.917
$L/Vol^{1/3}$	6.934	6.994	6.994	6.994
$WSA/Vol^{2/3}$	7.310	6.624	6.621	6.650

Figure 2 – Comparison of Principal Characteristics

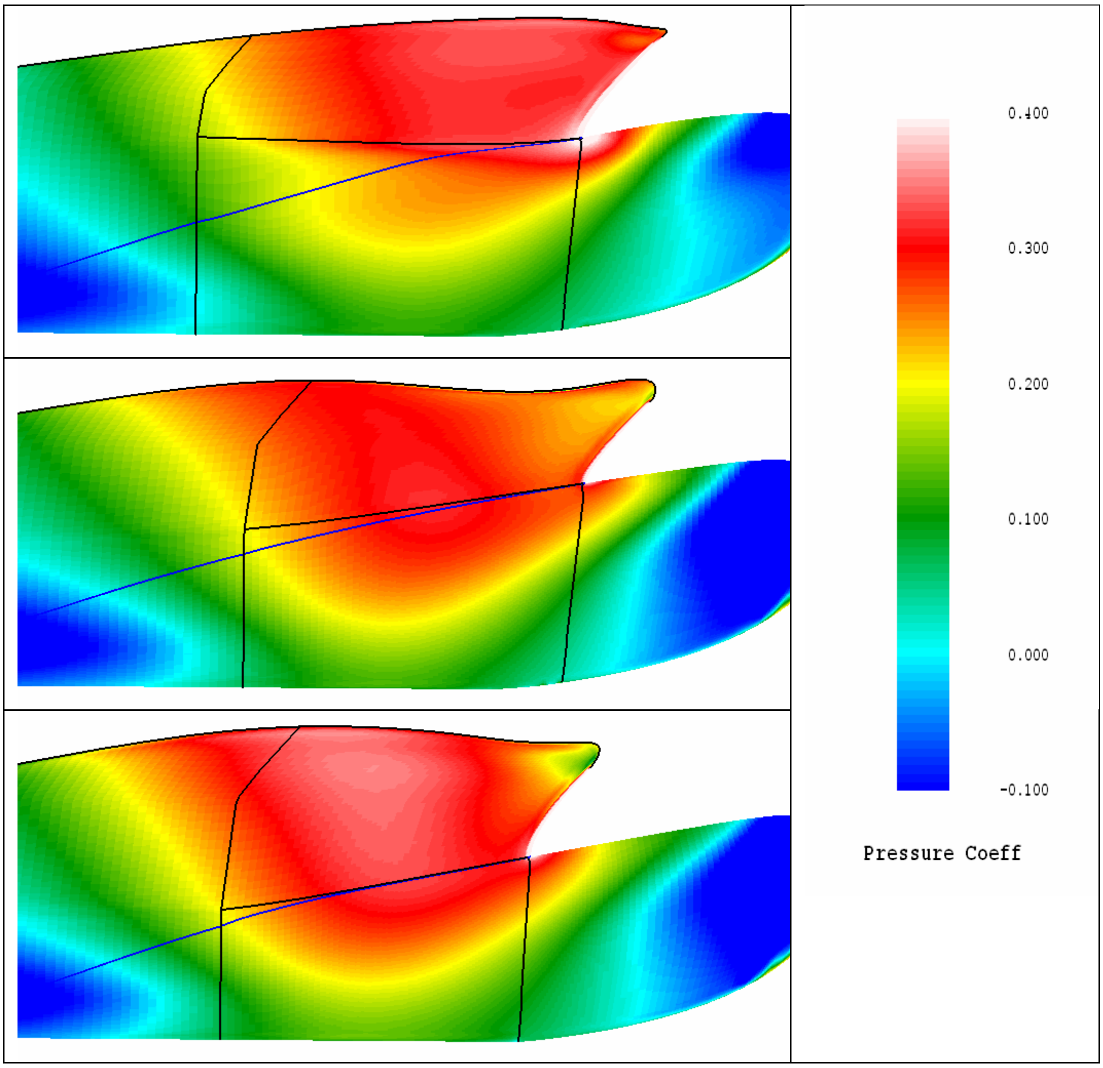

Figure 3 Pressure distribution with streamline at Vs =14 kn.

Speed [kn]	FN	C_R Itt1	C_R Itt2	C_R Itt3
12	0.233	1.92E-03	2.05E-03	1.96E-03
14	0.272	1.84E-03	1.99E-03	1.96E-03
16	0.311	1.94E-03	2.12E-03	2.14E-03

Figure 4 Computed Resistance Coefficients, C_R

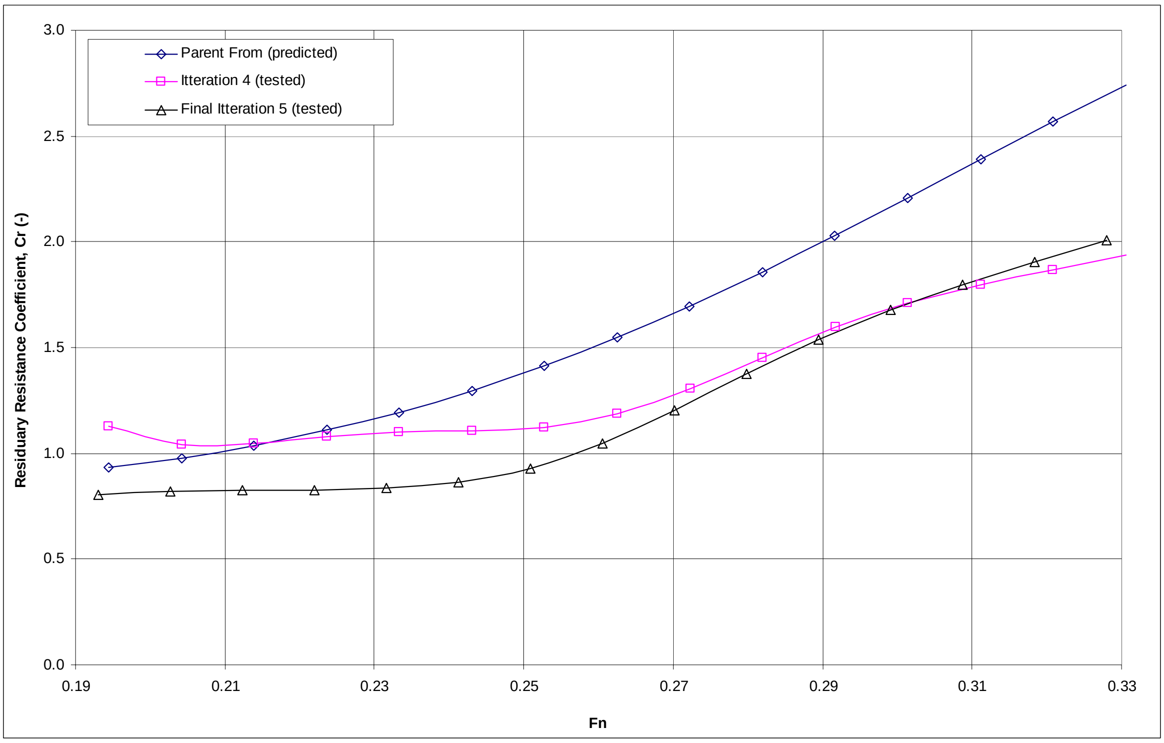

Figure 5 Final Measured Resistance Coefficients, C_R

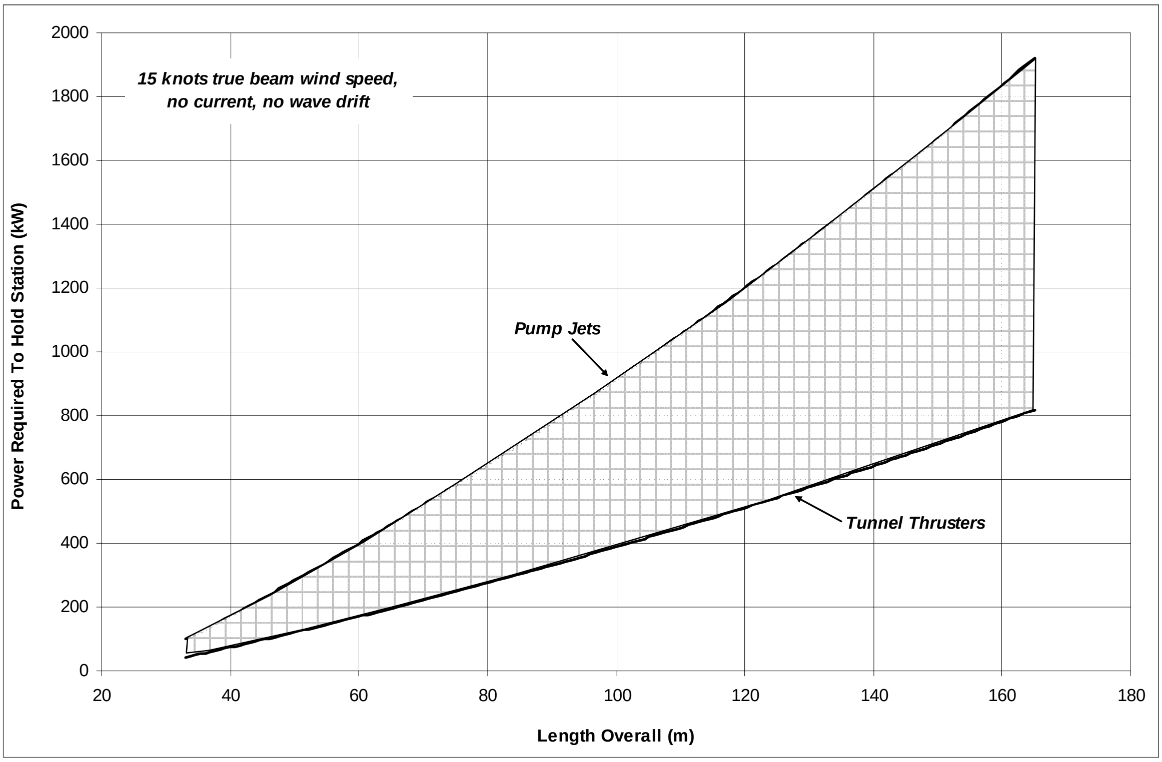

Figure 6, Power Demand To Hold Station, 15 knots True Wind Speed

Roll Reduction System Comparisons

	Conventional Roll Fins	At Anchor / Zero Speed Roll Fins	At Anchor / Zero Speed Rotary Fins	Bilge Keels	Roll Tanks	Anti-Roll Gyroscopes
Effictiveness at Anchor	- Low	+ Very Good	+ Very Good	+/- Moderate / Low	+ Good	+ Moderate
Effectiveness Underway	+ Good	+ Good	+/- Moderate / Low	+/- Moderate	+ Good	- Low
Internal Space Required	+/- Moderate	+/- Moderate	+/- Moderate	+ None	- Relatively Large	+/- Moderate / High
Ease of Retrofit	+/- Moderate	+/- Moderate	+/- Moderate	+ Easy	- Difficult	+ Easy
Impact On Displacement[1]	+/- Moderate / Low	+/- Moderate / Low	+/- Moderate / Low	- None	+/- Moderate	+/- Moderate
Impact on Power[2]	+/- Relatively Small	+/- Moderate	+/- Moderate / High	+ None	+/- Relatively Small	+/- Moderate / High
Noise and Vibration[3]	- Relatively Small	+/- Moderate / Small	+/- Moderate (no hard data)	+ None	+/- Moderate	+/- Moderate
Complexity / Ease of Maintanance	+/- Moderate	+/- Moderate	+/- Moderate	+ Low	+ Low	+/- Moderate
Cost of Installation	+/- Moderate	- Higher	- Higher	+ Low	+/- Moderate	- High
Technology Maturity	+ High	+ High	+/- Moderate	+ High	+ High	- Moderate / Low
Largest Application Available	+ 345m	+/- Approx 120m	+ 150m+	+ No Limit	+ No Limit	- 30m (modern gyro)[4]

Notes
1. - Depending on installation configuration. Retractable fins can lead to a large loss in buoyancy, coupled with system weight can lead to relatively high increase in displcaement
2. - Impact on power is intended to be general and include additional propulsive power and power to run the system
3. - All systems have been applied to yacht applications. With correct selection of equipment and sound treatments all systems can be made to operate to acceptablt noise levels
4. - Gyros have been installed on vessels up to 249m but using older, heavier, technology

Roll Reduction Systems Model Test Results

Significant Wave Height [m]	Standard Fins (Zero Speed™) Roll Reduction [%]	Magnus Effect MagLift™ Roll Reduction [%]	Variable Geometry Fin XT™ Roll Reduction [%]
0.50	78 - 92%	84 - 93%	82 - 90%
1.00	69 - 90%	78 - 92%	78 - 84%
1.50	58 - 81%	69 - 82%	

Note - Test in beam seas at resonant roll frequency, JONSWAP spectrum.

Figure 7, Qualitative and Quantitative Stabilisation System Comparisons