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SEEKING EFFICIENCY IMPROVEMENTS FOR A MOTOR-YACHT TRANSITIONAL HULL FORM

R G Shaw, Unitec Institute of Technology, New Zealand

SUMMARY

Experience in developing and refining custom high-performance race yachts unrestricted by rules has created an innovative approach to evaluating design challenges and considering potential solutions. This methodology has been applied to developing an efficient motor-yacht hull form with the potential for increased efficiency when operating in the transitional zone between displacement and planing speeds.

This paper looks at the challenges to efficiency posed by increasing performance of a 50 metre super yacht beyond displacement speed and into the high-resistance transitional speed range. A review of existing solutions to this problem are considered, including various hull forms, use of foils and developments in multihull design. It also proposes a concept hull design, influenced conceptually by some fast displacement multihulls, which offers a solution to improved efficiency in the transitional zone.

The concept hull is developed and compared to more conventional monohull displacement and planing hull forms. Particular attention is focused on the performance in the transitional speed zone. Factors influencing performance such as appendage drag, displacement-length ratio and power-to-weight ratio are considered. Further consideration is also given to other characteristics influenced by this design concept such as safety, comfort, maintenance and directional and static stability.

1. INTRODUCTION

There is a constant drive for improvement through innovation across all forms of technology. This is true also for super yachts, where continual design refinement is sought.

The focus of this paper is on a hull form that can offer improvements in efficiency in the transitional speed range between displacement mode and fast planing. Much attention and refinement has gone into optimising both displacement hulls and fast planning hull forms. However, the difficulty of designing or developing improvements to hulls which will operate in the transitional speed zone between displacement and fast planing has seen the optimisation of hulls operating in this zone to be somewhat neglected.

With advancements in technology both providing the ability to build lighter, stronger structures and enabling lighter and more compact power plants, a great opportunity exists to reconsider how we, as designers, can create a more efficient hull that takes advantage of these developments. Another advantage of a lower displacement is the reduced regulatory framework for super yachts with displacement under 500 gross tons.

This paper considers the weight reductions that could be achieved, and how those savings could translate to improved performance. The outcome is a higher quality, higher technology and higher specification motor-yacht that has improved efficiency, reduced running costs and is potentially more sustainable and environmentally friendly.

2. BACKGROUND

Recreational powerboat design owes much of its progress to the development of the diesel engine. Initially, recreational boats were limited to displacement speed operation due to horse-power, cost and weight limitations.

Following the Second World War, with the advancement in high-power engines, boat builders and designers were quick to adapt the new technology to recreational boats. The 1960s was a golden era of advancement for performance powerboats, during which time much of the development in fast planing hull forms that we benefit from today took place. From this time there has also been continued development in displacement hull forms, seeking to refine the concept to provide the best possible sea-keeping and efficiency characteristics.

This development hasn’t been isolated to monohull design; it has also produced some innovative solutions in multihulls, both power and sail. However, in spite of all of these developments there has not been a lot of advancement in motor yachts over 22 metres LOA. While some exceptions do exist, these tend to be outliers. The reality is this class of yacht is underrepresented in terms of achieving sustainable, efficient performance gains.

This paper looks at a potential hull form which, through the blending of advanced composite construction with modern power plants and innovative design, has the potential to advance the performance of this type of yacht.

3. DESIGN CRITERIA AND OBJECTIVES

For this new design it was important to frame its priority objectives. This is not intended to be a radical design that signals a major departure from current super-yacht form or function. The purpose is to explore an alternative approach to developing an efficient form that would also have positive consequences for the function of the motor-yacht.

Essentially, the main design criteria was for a 50 metre motor-yacht of moderate proportions, powered by a single screw and with the potential to efficiently operate at the upper end of the displacement speed range, approaching a Froude number of 0.6. A critical component of this was to target a lighter displacement than conventional motor-yachts of this size, through the use of composite construction throughout.

The key objective for this design is for the motor-yacht to have the potential to efficiently operate for extended periods at speeds considered higher than those associated with conventional displacement mode operation.

4. REVIEW OF CURRENT SOLUTIONS

Considering the development of a modern performance monohull which could exceed the traditional constraints of displacement operation, a range of current solutions were identified and considered. Strikingly, all of the options identified tend to fall in to either the conservative or extreme categories.

For displacement hulls, there are a few basic variations on the same theme, which are clearly very functional. At the other end of the range, where high speeds are the priority, this characteristic is often pursued at great expense. This expense is multifaceted and can be measured in financial cost (both build and operational), complexity and often also practicality and some would say aesthetically. Despite these developments, there is an apparent neglect of developing a hull form which combines the technologies currently available to achieve the performance advancements desired.

The use of foils on performance yachts is gaining attention, with excellent results achieved in dinghies such as the International Moth, ballasted monohulls such as the Quant 23 and IMOCA Open 60 class, and now the America’s Cup multihulls. Applying such foils to a motor-yacht is possible, although complex, and their performance is very speed-dependent.

For a vessel operating in the speed range being considered in this paper, it is considered that conventional lifting foils would not offer a significant performance enhancement. Certainly, when considered together with the added expense and complexity of such systems, it is not an attractive option for a vessel of this type.

Alternatively, the use of a single foil such as the Hull Vane® developed by Van Oossanen Naval Architects is a more practical solution for a vessel operating in this targeted speed range. This patented foil is positioned below the waterline, near the aft-body of a vessel, and is aimed at regaining part of the energy lost in the transom wave. It also influences the trim, and is designed to reduce the vertical motions of the vessel. [1]

This clever and effective appendage is best suited to achieve performance gains in the Froude number range of 0.2 to 0.7, which is similar to the speed range targeted by this design. The Hull Vane® shows great potential and has the advantage of the potential to be retrofitted to existing boats. However, the solution investigated in this paper also has the potential to achieve many of these same benefits without the complexity and exposure of adding a wing to the aft body of a vessel.

5. DESIGN ADVANTAGES

Principally, this motor-yacht design explores the concept of a canoe-stern underbody appendage which partially accommodates the engine and drive train. The purpose of this feature is to enable the engine and drive train to be positioned lower than the hull fair body. Through lowering the engine and drive train below the hull there are several potential advantages that can be achieved over a conventional hull and drive train geometry. It allows the potential to design a hull form that isn’t compromised by the need to accommodate the engine, drive train and appendages. This allows more freedom in the design of the hull, to better achieve an efficient hull form for the intended operating speed range.

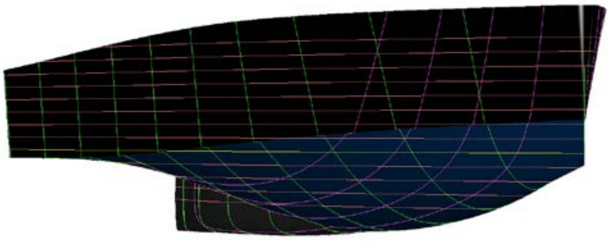


Figure 1: Candidate hull model, viewed from the starboard forward quarter.

By lowering the engine and drive train down into the underbody appendage it is possible to align the shaft angle with the direction of water flow, which gives a reduction in drag due to eliminating the exposed inclined propeller shaft and eliminating the need for a shaft support strut. Further performance improvements are gained through aligning the propeller with the water flow, improving the performance and efficiency of the propeller. With developments of the appendage geometry it could also be possible for the appendage to provide protection for the propeller and rudder in the case of grounding or a collision with a submerged object.

The engine appendage can also contribute to the directional stability of the vessel in the same way as a conventional deadwood or keel. This can be beneficial in quartering or crossing seas.

Through lowering the engine down into the appendage the vertical centre of gravity of the vessel is also lowered, improving the vessel's range of stability. A secondary potential advantage is to lower the accommodation space within the vessel to achieve a more comfortable motion at sea and improve the connection with the environment at rest.

6. PERFORMANCE

Several attributes are considered and refined in an effort to increase the performance profile of the motor-yacht. A single-screw propulsion configuration is combined with the propulsion appendage arrangement and minimising the structural weight through the use of carbon composite construction.

Utilising single-screw propulsion is a significant aspect of the weigh-saving concept of this yacht. In optimising the vessel to perform at the relatively low speed range of up to Froude number 0.6, the major contributors to resistance need to be considered and prioritised.

It is well understood that at this speed range, beam-to-length ratio and displacement have a significant impact on resistance, as do frictional drag, form drag, induced drag and aerodynamic drag. To reduce resistance and, probably most importantly, minimise wave drag, this design focuses on reducing displacement, a moderate beam-length ratio and a narrow angle of entry.

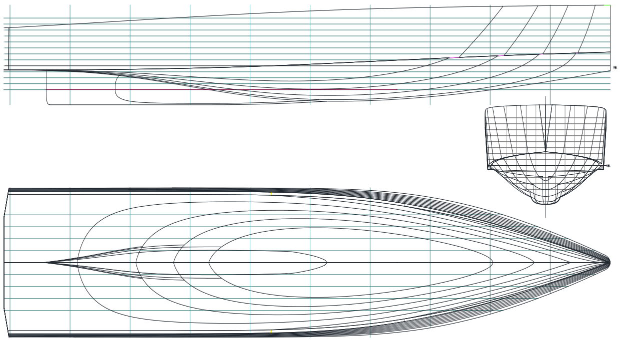
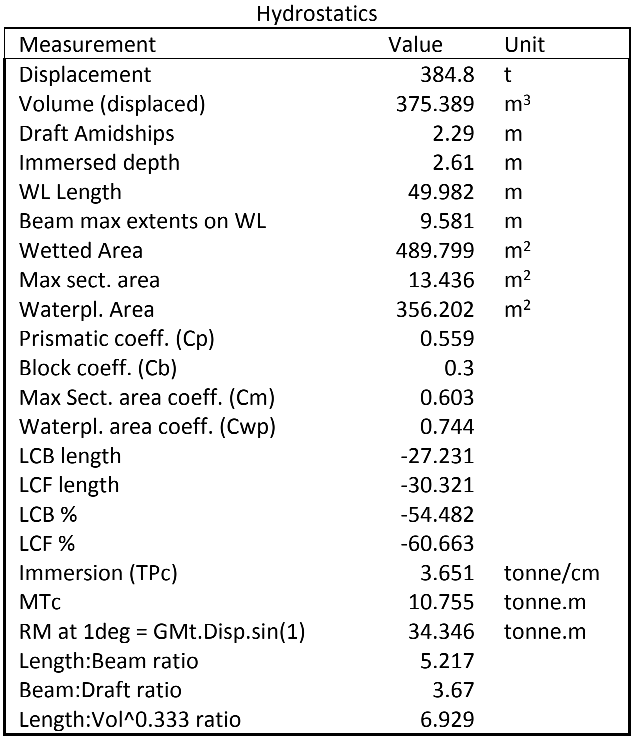


Figure 2: Candidate hull model lines plan.

Above Froude number 0.3 to approximately 1.2 is where the vessel enters the transitional speed zone, and it is here that wave drag is the most significant component of resistance. This hull form enables a warped plane hull with a fine entry and flat aft sections, to prevent squatting and maximise pressure recovery. It is possible to have the performance benefits of this type of hull but also benefit from reduced appendage drag and improved propeller efficiency due to the engine appendage.

It is accepted that there is some disadvantage due to the increased wetted surface area of the engine appendage. How-ever, given that wave drag is the major drag contributor at this critical speed range, it is a small price to pay in light of the advantages it offers.



Hydrostatics

Measurement	Value	Unit
Displacement	384.8	t
Volume (displaced)	375.389	m^3
Draft Amidships	2.29	m
Immersed depth	2.61	m
WL Length	49.982	m
Beam max extents on WL	9.581	m
Wetted Area	489.799	m^2
Max sect. area	13.436	m^2
Waterpl. Area	356.202	m^2
Prismatic coeff. (Cp)	0.559	
Block coeff. (Cb)	0.3	
Max Sect. area coeff. (Cm)	0.603	
Waterpl. area coeff. (Cwp)	0.744	
LCB length	-27.231	
LCF length	-30.321	
LCB %	-54.482	
LCF %	-60.663	
Immersion (TPc)	3.651	tonne/cm
MTc	10.755	tonne.m
RM at 1deg = GMt.Disp.sin(1)	34.346	tonne.m
Length:Beam ratio	5.217	
Beam:Draft ratio	3.67	
Length:Vol^0.333 ratio	6.929	

Figure 3: Candidate hull hydrostatics.

7. APPENDAGE DESIGN

A range of appendage design variations were considered. Inspiration was drawn from the Malcom Tennant canoe stern (CS) multihull design concept. [2] To achieve the positive benefit of the Tennant CS design, a different approach was necessary to adapt the concept to a monohull hull form.

The appendage solution applied in this design is an adaption of a proprietary low-drag ballast bulb section developed for racing yachts. This section has been modified to provide suitable proportions to contain the engine and drive train while morphing from the hull form, giving a fair transition. The aft sections of the appendage have also been modified to provide a profile that allows the lowest drag shaft exit and potential for the addition of a rudder skeg support.

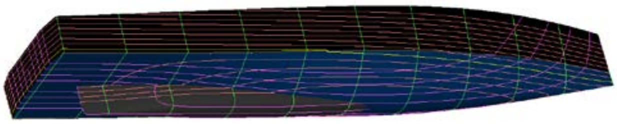


Figure 4: Candidate hull starboard rotation showing bilge appendage.

8. CONSTRUCTION

A critical component of the success of this hull form is the weight reduction achievable through the utilisation of building in carbon composites.

Advanced composites have been in use in the aerospace industry since the 1960s. Since then, the use of this construction method has become more widespread, and it has been undertaken in the marine industry for several decades now. In the 1980s, the use of advanced composites was adapted for boatbuilding in the production of IOR race yachts. It came to prominence in the construction of the New Zealand America's Cup challenger *KZ7*, which was runner-up in the challenger series in 1987.

Since then, advanced composite construction has been fully utilised and adapted to marine construction, building boats from the single-person foiling Moth to America's Cup yachts, both mono and multihull, and super-yachts. *Hetairos III*, at 66.4 metres LOA, is the largest super yacht so far built in carbon composite.

Improvements in processing techniques such as vacuum bagging, infusion and the use of pre-preg laminates has made composite construction more attractive and practical. These improved techniques have increased the quality and reliability that builders have been able to achieve.

Since it was first introduced to the marine industry, the cost of carbon composite laminate has dramatically reduced, making it a much more viable option for the construction of large structures. These improvements in cost, together with the weight savings, increased durability and longevity they offer, make composites a viable build medium for larger motor-yachts.

The use of composites eliminates the limitations on producing complex geometric shapes. This can be an advantage when designing both small and large surfaces, giving the designer unrestricted potential to explore more practical or aesthetically pleasing geometries.

While reducing the total weight of the yacht has obvious performance advantages, there are also other advantages in creating lighter components. The ability to reduce the weight of various hatches, doors and other movable components is significant. These advantages can range from reducing the need for electric/hydraulic operating mechanisms as well as reducing the potential risk of personal injury through operating these movable components.

Well-engineered and -manufactured composite structures are very long-lasting and are less susceptible to many of the corrosion risks prevalent in the marine environment. Composite structures have low fatigue rates and good resistance to chemical and electrolytic corrosion.

Traditionally, the complexity associated with building one-off composite vessels has made it not economically viable to pursue. The need to build a timber plug and finish it to a suitable standard to laminate the structure over was labour-intensive and added to the build time and workforce skills requirements. More recently, through the advancements in CAD-CAM technologies, larger CNC machining capabilities and the expanding capabilities of composite boatbuilders, it is now a viable option to build one-off composite boats. [3]

For this motor-yacht it is envisaged the structural surfaces would be built from carbon laminates and utilise a foam core. For the engine appendage, the use of monolithic construction is anticipated; the shape is well suited to this method but also it offers the most robust and resilient structure. There will be significant loads acting on this structure and it will need to be very stiff to ensure no vibration is caused through the propeller and drive train. It is also recognised that in the case of a grounding or collision with a submerged object, it is this part of the vessel that is likely to be at highest risk.

10. ANALYSIS

At the current concept stage, analysis has been conducted using three prediction analysis algorithms: the Savitsky pre-planing, Savitsky planing and the Holtrop methods.

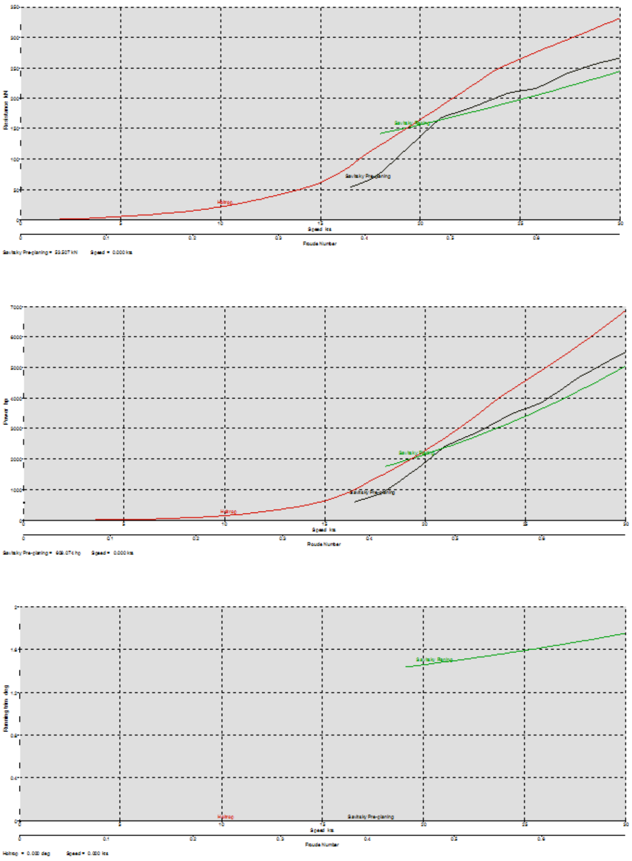


Figure 5: Analysis plots assessing resistance, power and running trim.

While applying these algorithms has provided useful and valuable analysis of the potential performance of this hull form, the application of these algorithms is considered solely a first step in analysing the performance of this concept. The next steps are to undertake extensive CFD analysis using the openFOAM software package. A focus on hull form, appendage design and the hull/appendage interface will be explored. Attention to ensuring an undisturbed flow of water onto the propeller will be a priority throughout.

Following a successful CFD study, development and testing of a scale model of the concept will be pursued.

Speed kts	Froude No. LWL	Froude No. Vol	Savitsky Pre Planing Resist (kN)	Savitsky Pre Planing Power (kW)	Savitsky Planing Resist (kN)
0	0	0	--	--	--
0.75	0.017	0.046	--	--	--
1.5	0.035	0.092	--	--	--
2.25	0.052	0.138	--	--	--
3	0.07	0.183	--	--	--
3.75	0.087	0.229	--	--	--
4.5	0.105	0.275	--	--	--
5.25	0.122	0.321	--	--	--
6	0.139	0.367	--	--	--
6.75	0.157	0.413	--	--	--
7.5	0.174	0.459	--	--	--
8.25	0.192	0.504	--	--	--
9	0.209	0.55	--	--	--
9.75	0.227	0.596	--	--	--
10.5	0.244	0.642	--	--	--
11.25	0.261	0.688	--	--	--
12	0.279	0.734	--	--	--
12.75	0.296	0.78	--	--	--
13.5	0.314	0.825	--	--	--
14.25	0.331	0.871	--	--	--
15	0.349	0.917	--	--	--
15.75	0.366	0.963	--	--	--
16.5	0.383	1.009	61.2	696.67	--
17.25	0.401	1.055	73.44	873.98	--
18	0.418	1.1	85.84	1065.98	--
18.75	0.436	1.146	112.24	1451.85	--
19.5	0.453	1.192	138.65	1865.24	167.43
20.25	0.471	1.238	164.09	2292.33	173.6
21	0.488	1.284	189.34	2743.01	179.93
21.75	0.505	1.33	203.89	3059.31	186.4
22.5	0.523	1.376	212.65	3300.86	193.03
23.25	0.54	1.421	222.58	3570.04	199.79
24	0.558	1.467	233.81	3871.25	206.68
24.75	0.575	1.513	243.1	4150.89	213.7
25.5	0.593	1.559	247.54	4354.79	220.85
26.25	0.61	1.605	252.81	4578.32	228.11
27	0.627	1.651	264.96	4935.44	235.49
27.75	0.645	1.697	277.13	5305.44	242.96
28.5	0.662	1.742	285.29	5609.18	250.54
29.25	0.68	1.788	293.13	5915.12	258.21
30	0.697	1.834	299.48	6198.17	265.96

Speed kts	Froude No. LWL	Froude No. Vol	Savitsky Planing Power (kW)	Holtrop Resist (kN)	Holtrop Power (kW)
0	0	0	--	--	--
0.75	0.017	0.046	--	0.15	0.08
1.5	0.035	0.092	--	0.56	0.58
2.25	0.052	0.138	--	1.2	1.86
3	0.07	0.183	--	2.05	4.24
3.75	0.087	0.229	--	3.12	8.07
4.5	0.105	0.275	--	4.4	13.65
5.25	0.122	0.321	--	5.88	21.3
6	0.139	0.367	--	7.58	31.36
6.75	0.157	0.413	--	9.5	44.22
7.5	0.174	0.459	--	11.67	60.4
8.25	0.192	0.504	--	14.17	80.63
9	0.209	0.55	--	17.05	105.88
9.75	0.227	0.596	--	20.42	137.34
10.5	0.244	0.642	--	24.41	176.82
11.25	0.261	0.688	--	29.29	227.32
12	0.279	0.734	--	34.91	288.99
12.75	0.296	0.78	--	40.77	358.61
13.5	0.314	0.825	--	47	437.7
14.25	0.331	0.871	--	54.44	535.15
15	0.349	0.917	--	64.17	664.03
15.75	0.366	0.963	--	77.27	839.61
16.5	0.383	1.009	--	94.6	1076.83
17.25	0.401	1.055	--	116.06	1381.16
18	0.418	1.1	--	131.69	1635.25
18.75	0.436	1.146	--	147.49	1907.83
19.5	0.453	1.192	2252.41	163.48	2199.19
20.25	0.471	1.238	2425.25	179.64	2509.58
21	0.488	1.284	2606.72	195.98	2839.29
21.75	0.505	1.33	2796.99	212.5	3188.57
22.5	0.523	1.376	2996.21	229.2	3557.7
23.25	0.54	1.421	3204.52	246.07	3946.94
24	0.558	1.467	3422.05	260.69	4316.35
24.75	0.575	1.513	3648.91	271.69	4639.03
25.5	0.593	1.559	3885.2	282.11	4962.82
26.25	0.61	1.605	4130.99	292.18	5291.22
27	0.627	1.651	4386.37	302.11	5627.3
27.75	0.645	1.697	4651.37	312.03	5973.61
28.5	0.662	1.742	4926.04	322.06	6332.26
29.25	0.68	1.788	5210.39	332.27	6704.94
30	0.697	1.834	5504.42	342.72	7093.03

Figures 5a and 5b: Analysis data showing resistance, power and running trim

11. CONCLUSION

Through study and observation of conventional solutions to designing hulls that operate in the transitional speed range came a curiosity to explore alternative hull forms that might better operate in this range. What has been developed is a concept only and needs much refinement to be developed into a viable solution with real advantages.

It is clear, however, that not only can this concept have potential for real performance improvements but that it can also impact on life on board, both at sea and at rest. It has the potential to both lower the vessel's centre of gravity and bring the accommodation space lower to the water, further improving comfort and the connection with the environment for both guests and crew.

While advanced composite construction has become a standard feature in performance boats, both power and sail, it is still quite uncommon in super yachts. There is potential to achieve significant improvements in performance through the application of these materials. Carbon composite construction has many advantages where higher performance is sort and is now a more viable construction medium for large, one-off boats than ever before. Through combining this advanced material with an innovative hull form and the benefits it offers, potentially significant performance gains can be realised in a practical, modern motor yacht.

11. REFERENCES

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12. AUTHOR'S BIOGRAPHY

Robert Shaw is a lecturer and academic leader at Unitec Institute of Technology in Auckland, New Zealand, specialising in yacht design and leading academic development and research in his department. He is also the principal of performance yacht design studio Shaw Yacht Design, leading collaboration and consultation on custom performance-yacht design projects.