THE SECOND CHESAPEAKE POWER BOAT SYMPOSIUM

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Recent Advances in Radio Controlled Model Testing

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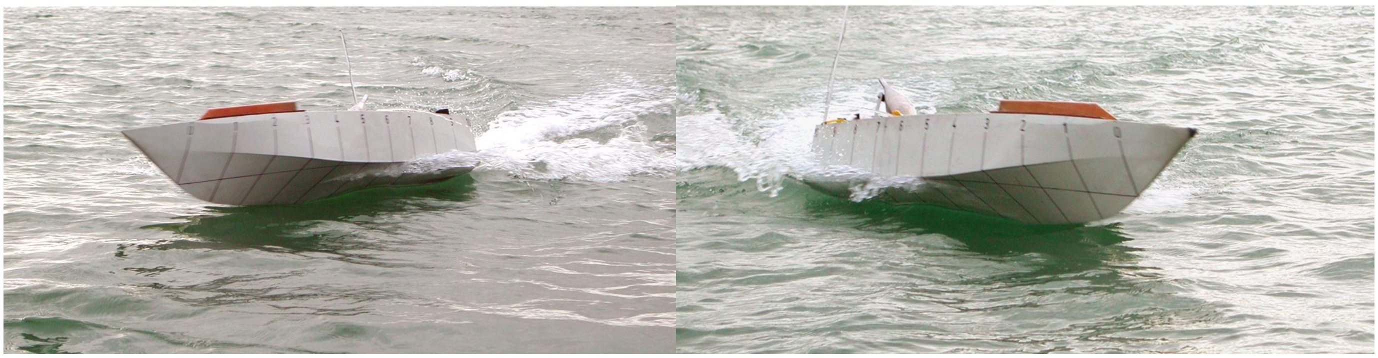

ABSTRACT

Self propelled models under radio control have been used for many years to assess the manoeuvring and handling of ships, and occasionally small craft. The limitations for testing small, fast craft have been linked to the low model weight required and the ability to install enough power, as well as the cost of modelling.

Recent advances in motor and battery technology, the availability of model water jet drives, and developments in small data logging and GPS systems have enabled cost effective modelling of very fast craft. Their handling characteristics can now be assessed accurately at an early stage of the design. This helps to ensure a successful boat, determine the acceptable boundaries of the design, or modify it to eliminate any problems found.

UNITS

SI units have been used in this paper, and the following conversion factors can be used to convert to those commonly used in the USA:

1 mm	= 0.039 inches	1 kg	= 2.20 lb
1 N	= 0.22 lbf	1 kW	= 1.34 HP

INTRODUCTION

Model experiments are a well established method of determining the manoeuvring characteristics of ships. They may be undertaken to ensure that contractual requirements are met, or because there is some innovation in the hull form or propulsion system that might affect the handling. The methods are well documented and understood.

Ship manoeuvring models tend to be large, with accurately machined model propellers, and therefore very expensive. The Wolfson Unit specialises in model testing of small vessels, and has developed methods of testing which are appropriate for projects with relatively small budgets, but which address the particular problems of small, fast vessels. These methods have been developed over the last 30 years, and were described in detail some years ago at the HISWA symposium (Deakin, 1998). Since that time, technological advances have transformed the modelling techniques and test procedures, enabling increased model speed and greater measurement accuracy.

THE PROBLEM

A scale model must be representative of the full scale boat in terms of its speed, weight, centre of gravity and inertia. Scaling laws dictate that the model weight is the full scale weight/scale^3, and small models need to be very light indeed. If most of the weight is in the hull and propulsion system, there is little ballast available to obtain the correct centre of gravity and inertia.

Larger models increase the cost and require larger expanses of water for the tests. This is a problem where large diameter turning circles must be performed, such as when evaluating directional stability at small helm angles. The cost increases not only because of the larger hull, but also because propellers, shafts and brackets become much more expensive. If the boat is driven by water jets, the scale will be limited by the availability of model jets, and this is likely to eliminate large model sizes.

The inefficiency of model propellers and jets, and the fact that skin friction is relatively higher at model scale, combine with the result that the power installed in the model must be greater than might be expected if one factors the power of the full size boat down to model scale.

Many of the components can be obtained from suppliers to the model boat enthusiasts market, but the size, weight and speed of a test model tend to be outside the normal envelope within which hobbyists operate, and the demands of a commercial client are different to those of an enthusiast. We are very familiar with the situation where the market offers components which almost do what we require.

MODEL CONSTRUCTION

Construction techniques for self-propelled models have included the traditional patternmakers' wooden "bread and butter" method, moulded GRP, and foam cut by machine or by hand. The most efficient and affordable method at present seems to be plank on frame construction. Our model builders use frames cut by hand or preferably by NC machine. The boat drawing is scaled to model size, the building frames selected, the planking thickness removed and the internal arrangement of longitudinals, bulkheads and platforms designed, all on the computer. The components are then cut, assembled, and planked with wood strips or wood based board products such as flexiply. The hull is faired and finished with a GRP tissue to ensure a rugged finish. This method has the advantages of very low weight and a thin hull, the latter being very useful when installing shafts and jets.

PROPELLERS AND JETS

Large ship manoeuvring models usually are fitted with accurately scaled propellers, and the model size may be dictated by the desire to minimise the propeller scale effects. To achieve this requires very large models, and the cost would be beyond the scope of most small vessel development budgets. The alternative approach frequently taken at the Wolfson Unit is to use a very simple model propeller which acts as a thruster rather than a model of the full size propeller. The propeller diameter is modelled correctly, and its speed of rotation is adjusted to achieve sufficient thrust, so the flow upstream and downstream of the propeller is representative. This enables the model size to be chosen on the basis of other practical considerations, and propeller costs are minimal.

Propellers can be cast, machined, or even simple twisted plates attached to a hub. The latter solution, although the cheapest, is unlikely to have the strength to transmit the power required for fast models. Some of the propellers sold for the model boat enthusiast may not be strong enough to deliver the required power, but in the UK it is possible to obtain a handed pair of propellers which are cast in brass, machined then hand finished to a good standard for less than \$100. See Figure 1.

Figure 1 Twin screws in tunnels on a 30 knot motor yacht

Our earliest tests with water jets were conducted when injection moulded plastic jet units came onto the model boat market. These were suitable for models of small craft such as pilot boats and rescue boats, in conjunction with the electric motors available at the time which delivered less than 1kW. For larger models and higher speeds, these units were inadequate but alternatives became available which offered larger diameter jets and more robust construction.

There have been a number of stages in this progression with jets from various suppliers, and many mechanical failures of impellers, shafts and bearings when the units did not live up to expectations. At present we use jets with a diameter at the impeller of 50mm and an outlet diameter of 32mm. They have a composite body, a five bladed titanium impeller and sealed high grade stainless steel bearings. They can absorb up to 4kW of power with an efficiency of around 35%, and a thrust of 145N at 14,000rpm. See Figure 2 and Figure 3.

It is important to model the jet intake accurately, so this is done by the model builder and the water jet unit is fitted some distance above the hull bottom, where the duct sizes are compatible.

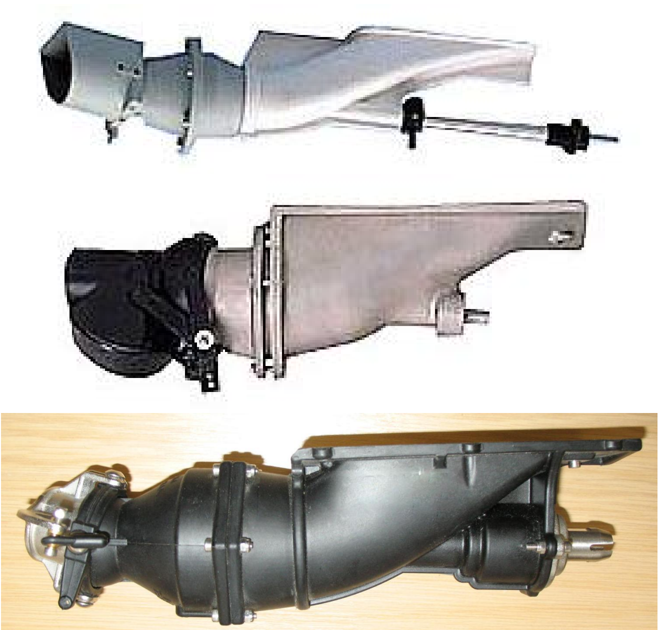

Figure 2 A progression in water jet manufacture: upper jet 0.5kW, mid jet 1kW, lower jet 4kW

Figure 3 Titanium jet impeller of 50mm diameter

Figure 4 Intakes on a triple jet installation

PROPULSION POWER

There are two principal options for powering small models: electric motors or internal combustion engines. The former may be an essential requirement if testing in an indoor facility, but sometimes the high power requirements for fast models can only be met with engines.

There is a wide range of internal combustion engines available for the model boat, car and plane enthusiasts, and these offer very high power to weight ratios. A tank of engine fuel offers much greater operating time than a battery of the same weight, and these factors have dictated their use on many projects. The two principal types are glow plug and 2-stroke engines. Both have been used at the Wolfson Unit, and Figure 5 shows an example installation of the latter. Direct driving to propellers or jets is not ideal for the experimenters because high thrust is generated as soon as the engine fires, but when this model was tested there were no suitable clutches available for the drive system.

The popularity of engines among model racing enthusiasts isn't shared by those of us engaged in commercial testing. Fuel leaks are difficult to avoid completely, and the model can become very messy in a prolonged test programme. The engines run at very high speeds, and all parts of the propulsion system must be strong enough to withstand the starting torque. They have the potential to induce considerable vibration, often resulting in fatigue failures of lightweight model components.

In a twin engine installation, the engine speeds need to be the same to ensure a balanced propulsion for manoeuvring tests. This can be achieved by adjusting the throttles to the same setting so that the engines are running at similar speeds. They will then synchronise their speeds naturally by tuning their vibrations to match each other. This is a very useful characteristic, but not sufficient to tempt the experimenter to choose them rather than electric propulsion if appropriate motors can be found.

Figure 5 Twin water cooled 2-stroke engines with direct drive to water jets in a 22m, 50 knot patrol boat

Small electric motors offering power of 0.5kW were the standard for many years. These had plastic bodies whose deformed shapes revealed when the motors had overheated on a test run. They were superseded about 15 years ago by metal clad motors with higher rated power, but they didn't often live up to the claims and many failures were suffered. Water-cooled motors were the next significant step for the motor manufacturers.

Water cooling is reasonably straightforward, and has been employed on engines and speed controllers as well as motors. It is achieved with one or more small scoops fitted in the stern of the model, small flexible tubes connecting them to the motors, and a simple overboard discharge. All additional systems add weight and complexity though, and the scoops present a feature that is not there at full scale, so may bring some uncertainty when analysing a manoeuvring problem. Early installations used scoops which protruded beneath the hull, but flush designs, as in Figure 1 and Figure 4, have been found to be adequate.

Figure 6 Twin water jet patrol boat under test at 50 knots

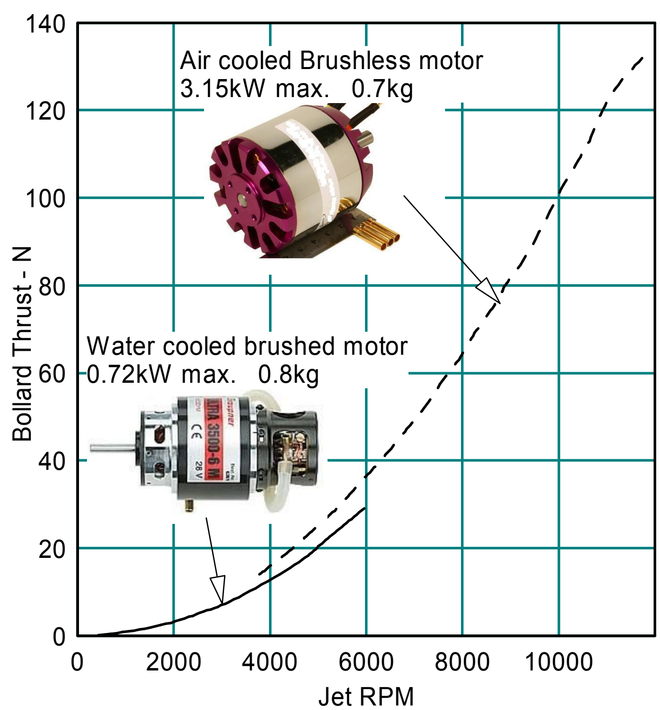

Figure 7 Measured jet thrust for 2 motors with a 30V, 2.6kW power supply

These incremental gains represented useful progress, but we were continually struggling to meet the needs of our customers who wanted to test faster boats. A breakthrough has come recently with the availability of brushless motors, which are highly efficient and have a very high power to weight ratio. Motors of a suitable size came onto the market about 2 years ago. Those in use at present provide 3.1kW with a weight of less than 1kg. They have an efficiency of around 94%, compared to brushed motors which operate at around 86%, and this eliminates the need for water cooling. An illustration of the degree of progress that they represent is given by Figure 7. This shows the thrust measured with a model tethered in the towing tank. The thrust delivered by the jets when under way is greater than the bollard thrust, but these results are representative of the difference in power that separates these two types of motor. These examples have similar weights and size.

BATTERIES

Traditional lead-acid batteries are bulky and heavy, but because their location relative the other model components is not restricted, they can be regarded as ballast and located to obtain the desired centre of gravity and inertia. Up to about 10 years ago, most of our electric powered models were fitted with sealed 6 volt cells connected in series to obtain the required voltage; usually 24 or 30 volts. With this arrangement there was adequate scope to adjust the ballast longitudinally, transversely and vertically as required.

As they are discharged, the voltage falls gradually to around 60% of its original value, and this is a problem when constant speed trials are required. It was common to have three sets of batteries which could be recharged on site and used in rotation. As higher speeds and powers demanded higher currents, the existing batteries proved unable to deliver the stated capacity. Better performance can be obtained with a single large battery rather than an arrangement of smaller ones, but this eliminates the possibility of distributing the batteries to ballast the model.

Nickel-cadmium (Ni-Cd) batteries are popular in the hobby field, and they offer a higher power to weight ratio, so have been used when weight restrictions prevented the use of lead-acid. They are more expensive however, and their capacity is low, so they are not ideal for tests of long duration. Like lead-acid, their voltage drops steadily as they are discharged. For many years they were the only practical alternative, but battery technology has brought more options recently.

Our most recent test model was powered by Lithium polymer batteries that supply 37 volts with a capacity of 10 Ampere hours. Their power to weight ratio is about four times higher than that of lead-acid. Another great advantage for commercial model testing is that their voltage drop is only about 10% as they are discharged.

Figure 8 shows how the various battery types compare. It reveals that new technologies are developing which might increase the possibilities of greater power in the near future, if they become available at a suitable price.

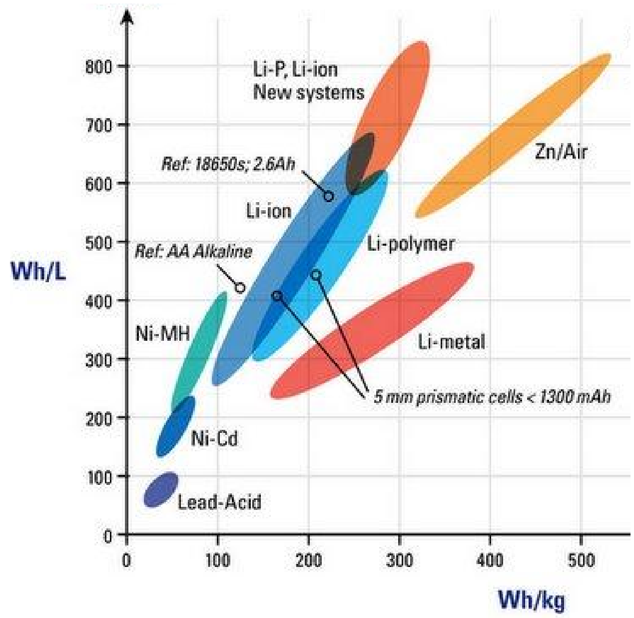

Figure 8 Comparison of batteries in terms of power to weight (x-axis) and power to volume (y-axis)

An example of the impact of this recent progress in batteries is presented in Table 1 and Table 2. The first table shows the sizes, speeds and weights of models of a 22 metre vessel at different model scales, with values for the full scale vessel included for reference. An estimate has been made of the weight of the basic model hull structure, and it is clear that this forms an increasing proportion of the total weight as model size reduces. Larger models therefore provide greater flexibility in outfitting, and facilitate the task of obtaining the correct centre of gravity and inertia. The required motor power is estimated assuming an overall propulsive coefficient (OPC), or total efficiency, of 20%. A voltage of 30v has been assumed in all cases because this usually is a practical value, and this gives rise to very high currents to supply the power required for the larger models.

In the second table, for three battery types, a comparison is made of the weights of batteries required at each model scale. The available ballast noted in the table is the percentage of the total model weight that is available for outfit and ballast, after deducting the model structure and battery weights. A value of about 40% usually is required to install the propulsion gear, control gear, instrumentation, and leave enough ballast to enable fine adjustment to the correct centre of gravity and inertia. The running time is also tabulated in each case, and we normally demand a minimum running time of 10 minutes in order to conduct effective trials. Where the available ballast or running time are inadequate the table is shaded, with a lighter shading indicating examples which are marginal. In this example, only two cases comply with both of these requirements, and these are shown in bold type. This vessel could not be modelled with lead acid batteries, and probably could not be modelled with nickel-cadmium or nickel-metal hydride batteries Lithium-polymer batteries, however, offer the option of testing at a scale in the range 1:10 to 1:12.

SPEED CONTROL

There are a wide range of electronic speed controllers available for radio controlled models, and their development has had to keep pace with increasing model performance and higher power. Electrical currents of 50 to 100 Amps are common. Brushed motor speed controllers vary the supplied power by chopping the supplied voltage over a range of mark space ratios. Brushless motors benefit from speed controllers that are based upon a three phase system. At any instant only one of the three wires connected to the motor is providing voltage, the two remaining are providing feedback information to the speed controller which allows the timing and thus the efficiency of the motor to be fine tuned in real time.

Another aid to maintaining a constant trials speed is a voltage regulator. We use a device that can handle power of up to 1.6kW, regulating the power to the motor irrespective of the battery voltage. It has an efficiency of 92%, weighs 1.65kg, and is rather bulky, so the benefits come at a cost but it has proven valuable in recent projects. For higher power requirements we have successfully wired them in parallel.

Model Scale	LOA	Model beam	Model speed	Resistance	Total model weight	Model structure weight	Effective power	Required motor power (20% OPC)	Motor voltage	Motor current
	m	m	m/sec	N	kg	% of total	kW	kW	v	A
Full	22.0	5.4	25.7	87800	50000		2258	11291		
8	2.8	0.68	9.1	171.5	97.7	17	1.56	7.80	30.0	259.9
10	2.2	0.54	8.1	87.8	50.0	26	0.71	3.57	30.0	119.0
12	1.8	0.45	7.4	50.8	28.9	38	0.38	1.89	30.0	62.9
14	1.6	0.39	6.9	32.0	18.2	52	0.22	1.10	30.0	36.7
16	1.4	0.34	6.4	21.4	12.2	68	0.14	0.69	30.0	23.0

Table 1 Example parameters for different scale models of a 22m fast craft

	Lead acid			Nicad / NiMH			Lithium polymer		
Model Scale	Battery weight	Available ballast weight	Running time	Battery weight	Available ballast weight	Running time	Battery weight	Available ballast weight	Running time
	kg	% of total	minutes	kg	% of total	minutes	kg	% of total	minutes
8	25.0	57.5	1.4	17.5	65.2	4.0	16.0	66.7	6.0
10	25.0	23.6	3.0	17.5	38.6	8.8	**16.0**	**41.6**	**12.0**
12	25.0	-24.4	5.7	17.5	1.5	16.7	**6.0**	**41.2**	**10.0**
14	16.0	-39.6	9.8	11.2	-13.2	28.6	2.7	33.7	14.0
16	16.0	-98.7	15.0	11.2	-59.3	45.7	2.7	10.3	20.0

Table 2 Comparison of available ballast and running times for three battery types to power the models in Table 1

One of the benefits can be seen by comparing Figure 9 and Figure 10, which show the tracks of two models executing steady turns. The first example had no speed regulation, and the speed decreased by nearly 30% as shown in the inset graph, as the battery discharge gave rise to a lower voltage to the motors. The turning circle diameter reduced as the speed decreased, so that determination of the turning circle characteristics was less reliable than one would wish for. In the second example, the turning circle diameter is constant. The circles migrate slightly across the test site because of a north-easterly wind, but it is a simple exercise to derive the turning circle dimensions to a high level of accuracy.

GPS TRACKING

Several methods of model tracking have been used in the past, including cameras tracking on-board lights or manual tracking using scopes trained on a mast. Such methods require two shore bases and analysis of the two bearings to derive the model track. At the Wolfson Unit a number of test methods were developed that dispensed with the need for tracking, but one cannot define turning circle parameters without it.

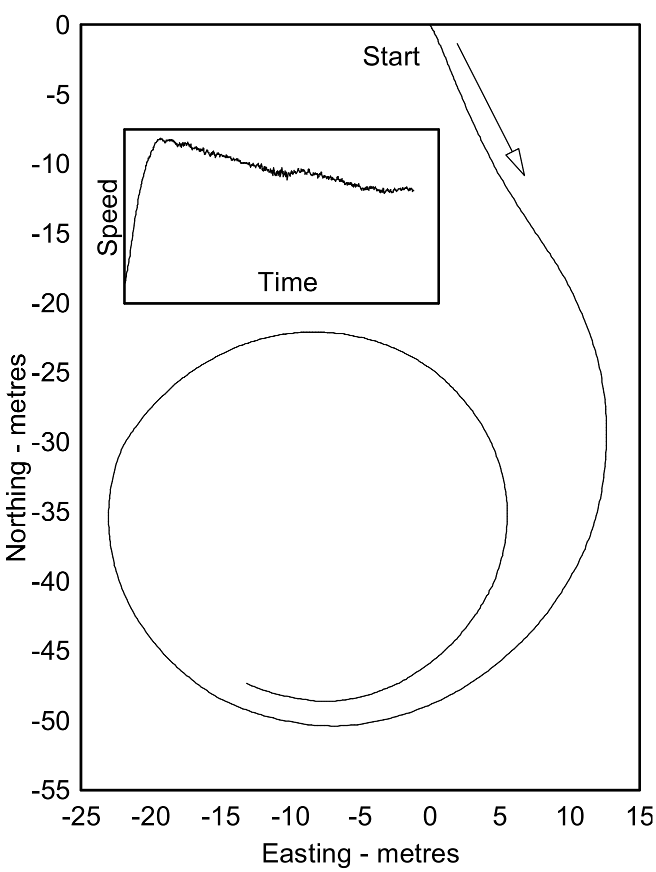

Figure 9 GPS track of a model in a steady turn

Modern GPS systems which rely solely on satellite tracking are sufficiently precise for model testing without the need for additional shore based reference stations. The tracks plotted in Figure 9 and Figure 10 were derived directly from GPS raw data records without any adjustment or smoothing of the values.

DATA LOGGING

Early data logging systems, using tape as a recording medium, were heavy and vulnerable in the damp model environment. The alternative was data telemetry to a shore based recorder but, while it offered a weight saving, it could be costly and unreliable.

Recent progress includes the introduction of solid state recording equipment, and we now use a combined GPS and data logging device. This was developed to meet the demands of racing car teams and offers the GPS tracking facility, giving speed, position, and heading. It can accept up to sixteen analogue input channels at acquisition rates of up to 100Hz. Typically we use it to record measurements of helm angle, accelerations in three axes, yaw rate, and roll rate, but of course it may be used to record signals from other transducers as required.

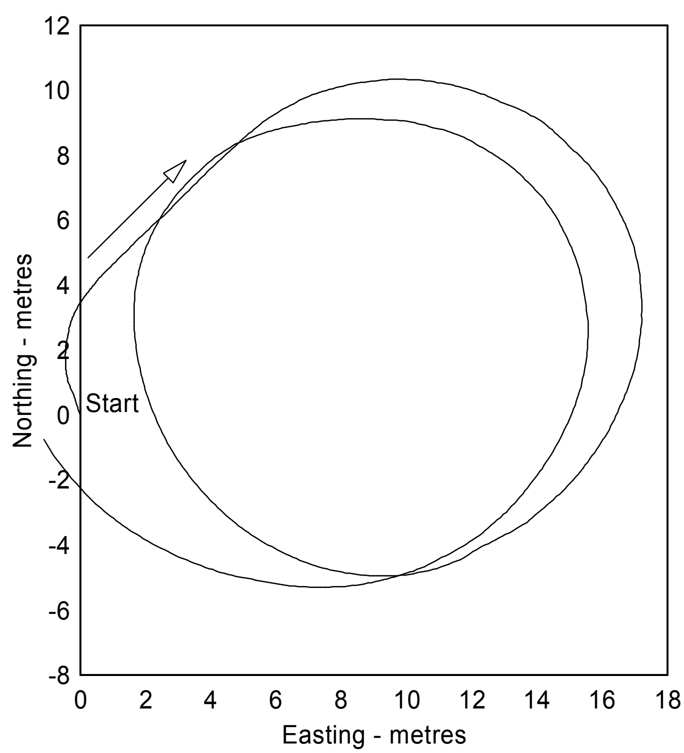

Figure 10 GPS track of a model in a steady turn, with voltage regulation giving constant speed

The recording medium is a simple and reliable compact flash card, and the total weight is only 2.2kg. Modern data telemetry based upon the 2.4GHz frequency is a reliable way of transmitting data to the shore but the advantage of being able to see real time data is of limited value when the full concentration of the helmsman is required to drive the model, especially a model operating at high speed.

Figure 11 presents another example of model test data, from a standard 20/20 zig-zag manoeuvre on a model representing a full scale speed of 34 knots. In this trial the helm is put over to 20 degrees until the heading has changed by 20 degrees, then the helm is put to 20 degrees the other way. The data were obtained from a rotary potentiometer to measure the helm angle, and a yaw rate gyro, integrated to obtain the heading. Again, these are raw data acquired at 20Hz with no adjustments or smoothing applied.

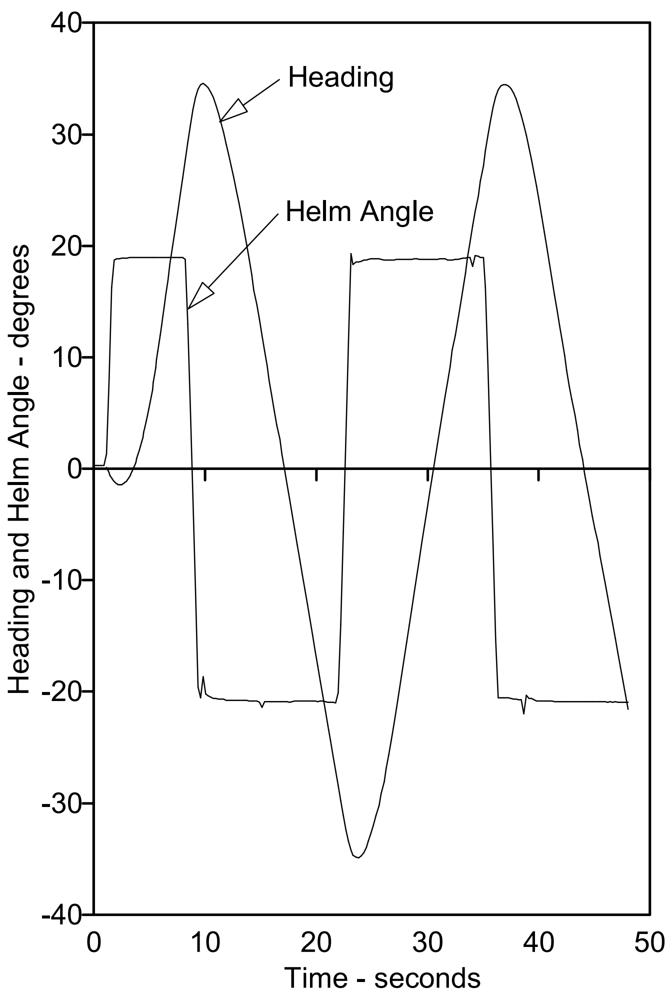

Figure 11 Measured results for a 20/20 zig-zag manoeuvre

The time taken for the helm response, combined with the dynamic behaviour of the boat, result in an overshoot in the heading, which is an important handling characteristic. In this example the heading increased to about 35 degrees from the original course; an overshoot of 15 degrees, but some of that overshoot is due to the fact that there was a slight delay between the heading increasing to 20 degrees and the experimenter changing the helm. The data are presented in full scale time but the model was at a scale of 1:16, so the time at model scale was ¼ of that shown here. The lag between the heading and helm command represented about 1.2 seconds at full scale but was only 0.3 of a second on the model. This time is limited by the model operator's ability to respond following an observed heading change. By careful analysis of the data following the trials it is possible to adjust the results to eliminate known errors such as this, but it is a good example of the difficulties of conducting accurate and repeatable trials on very fast boats. An on-board autopilot could be programmed to make the helm change at the correct time, but this would add weight and considerable complexity and cost to the model outfit. Cost effectiveness of the tests is always a consideration.

VIDEO RECORDING

Video recordings have long been an important feature of the tests, to enable careful analysis of the behaviour, for the client's inspection and for marketing purposes. Recording media have changed, and cameras have improved, enabling a much higher quality product, but these advances in technology have not affected the test methods significantly.

Figure 12 Two compact cameras mounted on a mast for on-board video recording

The availability of small solid-state video recorders, such as those incorporated into compact sized digital cameras, has brought the option of on-board video recording to small models. Miniature video cameras have been available for some years, but good recording equipment tends to be heavy. Some experimenters have used telemetry to send the signal to a shore based recorder, but this increases the complexity and cost. The compact camera is a simple, reliable, self-contained solution which is light in weight, inexpensive and readily available in the shops. Some are even waterproof.

There are a number of uses but, primarily, an on-board camera enables an accurate measure of the heel angle during manoeuvres. This can be measured from a shore based camera but accuracy is limited and the measurement is restricted to the occasions when the model is heading directly towards or away from the camera. Alternative devices, such as miniature roll gyros can be fitted, but these measure the roll rate and the integration process required to derive the roll angle is corrupted by motions in other axes, such as pitch, which affect the constants of integration.

RADIO CONTROL

Model enthusiasts rarely need to know the precise calibration of their controls, so early radio control systems had to be customised, to enable repeatable helm angles to be selected for example. Steering systems comprising servo winches, control lines and pulleys, tillers of adjustable length, and micro-switches were contrived to achieve the repeatable and precise helm angles required for reliable tests. Modern radios feature programmable controls, with variable rates, which simplify the calibration process considerably and eliminate the need for anything more than a good quality servo.

In the UK the traditional radio frequency for model boats and cars is 40MHz, but this frequency is vulnerable to interference from on-board electrical noise, or from other sources nearby. Many early high power models suffered from considerable interference from arcing across the motor brushes. In some cases the range of the radio gear was reduced to 10-20m as the signal to noise ratio decreases with distance from the helmsman. The most effective solution was to move the receiver, servos and their wiring as far away from the motors as possible in the hope that this would give the model the required range from the helmsman. In the last few years came the introduction of 2.4GHz radio systems, which have been developed to eliminate such interference and so provide much improved reliability. Although they share the frequency with numerous other devices, including telephones and computer networks, they incorporate sophisticated methods of effectively locking the receiver and transmitter together.

Figure 13 Model of a 26m motor yacht turning at 30 knots

Figure 14 The award winning Ermis II, tested extensively for the designer Rob Humphreys

CASE STUDIES

Case 1 - Design Boundaries for Directional Stability

It is well known that directional stability and other handling characteristics are dependent on the trim and transverse stability. A twin screw pilot boat, which required good handling characteristics in rough seas, was tested at an early stage of the design. Small angle zig-zag tests were used to determine quickly whether the configuration was stable or unstable. This method does not give the same level of detail as a Dieudonné spiral trial in quantifying the directional stability, but reveals whether the boat is stable, unstable or marginal. Dieudonné spirals require considerable time and battery life, and a large area of water. This alternative method was sufficiently accurate to define the boundaries of acceptable loading conditions in terms of the vertical and longitudinal centre of gravity. With a high centre of gravity the boat was directionally unstable and with a moderate VCG the stability depended on the trim. The data enabled the designer to fix the general arrangement and distribution of weights with confidence.

VCG - metres above Base	LCG – metres forward of design		
	-0.2	Design	0.2
1.5	Stable	Stable	Stable
1.8	Stable	Stable	Poor
2.0	Unstable	Unstable	Unstable

Table 3 The effect of centre of gravity on directional stability

Case 2 – Testing for a Tendency to Broach

Radio controlled models can be used to assess tendency to broach in following seas, A 51m triple jet driven patrol boat was tested in following seas in a matrix of wave heights and periods with the results shown in Table 4. The tests were conducted in steep regular waves, with the model operated at speeds close to the wave speed, creating the conditions most likely to cause broaching. This model was not instrumented because it was adequate to observe and monitor the response to the controls in the controlled environment of the seakeeping basin. The handling proved adequate for the seastates specified for that particular vessel, but higher waves were used to explore the limitations of the design for future projects.

Run	Loading condition	Wave height	Period	Comments
	tonnes	metres	seconds	
1	246	1.5	5.26	Good control
2	246	1.5	5.88	Good control
3	246	2.5	5.26	Broached twice
7	275	1.5	5.88	Good control

Table 4 Manoeuvring in waves – Test results

Case 3 – Minimum Rudder Size for Good Control

A twin screw 15m motor yacht, developed by a well known experienced designer, required good close quarters handling and good controllability in heavy seas. A radio controlled model was used to assess its performance in calm water and in a seakeeping basin, with the conclusion that the rudders had insufficient area to provide adequate calm water turning capability and control in following seas. The tests in waves were qualitative in nature, relying on the experimenter's ability to control the boat, as in Case 2 above. The tests were re-run using a selection of larger rudder sizes until the minimum rudder size to provide satisfactory handling was identified. Figure 15 shows the stern gear of the model with graduations marked on the rudder representing the different tested rudder areas.

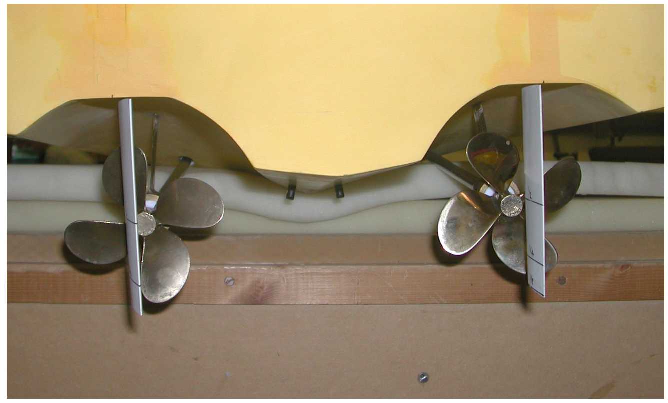

Figure 15 Stern gear on a 15m motor yacht

Case 4 – Maintaining control at high speed

A shipyard required confidence that a proven design of fast patrol boat would perform well with increased power, operating at higher speeds than previous boats. A model was tested at 45 knots, the maximum speed of the existing boats, and at 50 knots, the required speed of the new boat.

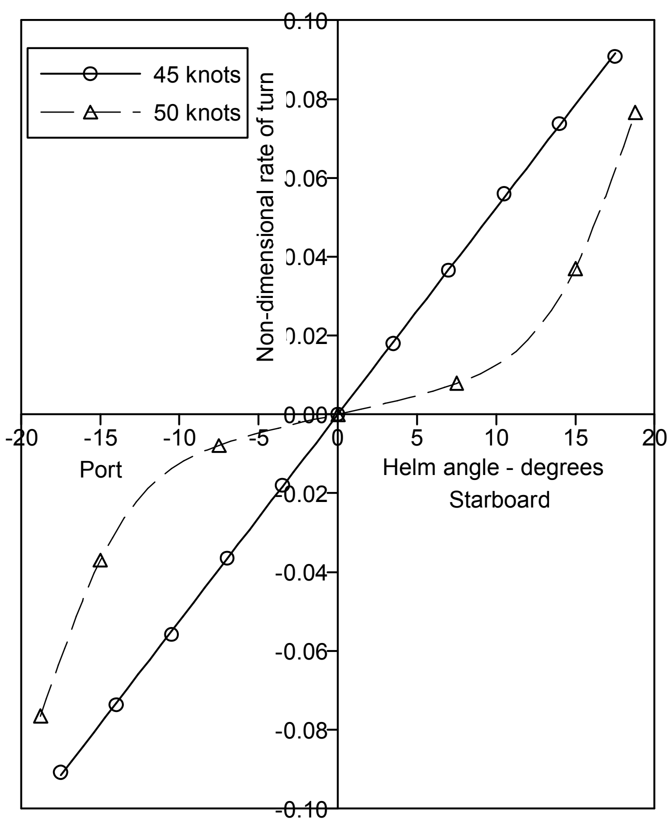

Figure 16 Effect of speed on the variation of rate of turn with helm angle

The model was driven by twin water jets and equipped with GPS tracking. Figure 16 presents the results of the tests in terms of the rate of turn in response to different helm angles. It is clear that the handling characteristics are very different at the higher speed, with the relationship between rate of turn and helm angle no longer linear. With a lower rate of turn for a given helm angle, the turning circle diameter was larger, but the model exhibited no directional instability and the handling remained satisfactory.

CONCLUSIONS

The marine industry has been able to meet recent demands for higher speed with lighter materials, improved engines and more efficient propulsion systems. In parallel with these technological advances, there has been progress in the performance of electric motors, batteries, model water jets, control gear and instrumentation. This has enabled scale modelling of fast craft to remain the most cost effective means of ensuring that a new design will perform well.

Model tests can highlight potential problems with handling and control, and define the design boundaries or limitations of a boat.

If a boat is built with, or develops, an undesirable handling characteristic, this can be analysed with a scale model and potential modifications can be assessed cheaply and quickly.

In either case, the use of models gives the designer and owner the confidence to make the investment to build or modify the boat with minimum risk.

REFERENCES

Deakin, B., “Model Tests to Assess the Manoeuvring of Planing Craft”, 15th HISWA Symposium on Yacht design and Construction, Netherlands, 1998