SAILING SHIP PERFORMANCE - CORRELATION OF MODEL TESTS WITH FULL SCALE

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SUMMARY

Correlation of model and full scale data has been addressed by many researchers, but it is unusual that the opportunity arises to examine the data for a sailing ship. A comprehensive model test programme conducted during the design of the sailing ship "Tenacious" provided predictions of the motoring performance, sailing performance, manoeuvring and motions at sea. This paper presents a comparison of the predictions with measured and anecdotal evidence gathered during the first year of service.

AUTHOR'S BIOGRAPHY

Barry Deakin is a Senior Engineer with the Wolfson Unit for Marine Technology & Industrial Aerodynamics at the University of Southampton. He joined the Unit in 1978 and has specialised in model testing and stability.

He has been responsible for developing the stability standards for sailing vessels that are used in the UK Codes of Practice.

1 INTRODUCTION

The model tests conducted for this project have been described in detail elsewhere by the author [1], and so this paper presents only a brief account. Similarly, the Wolfson Unit's standard experimental procedures have been described by the author and others, and appropriate references are provided for each aspect of the tests.

The Wolfson Unit specialises in model tests on racing yachts and large cruising yachts, and routinely conducts towing tank and wind tunnel tests to quantify their sailing performance. This project provided an unusual opportunity to study some additional aspects of the performance of a large sailing vessel, and the further opportunities to study the correlation with full scale are seen as an important bonus.

2 BACKGROUND – S.V. "TENACIOUS"

The Jubilee Sailing Trust is an organisation offering opportunities for disabled people to sail on equal terms with the able-bodied. They operate a barque of 41 metres length on deck, the Lord Nelson, which entered service in 1986. After several very successful years with that vessel, and with a very high demand for berths, the Trust decided to expand its operation and build a second ship of wood.

Tony Castro was commissioned to design the vessel, which was to be built in a shipyard set up by the Trust specifically for the project.

Much discussion took place within the Trust regarding the preferred hull form. In addition to a range of design data, the test programme was designed to provide information to enable a decision between a full length keel typical of traditional sailing ships, or a more contemporary form with a shorter keel of which Lord Nelson is an example. Following these tests the long keel design was selected, and the result is a three masted barque, with a traditional hull form much admired by her captain for its seakeeping and handling qualities.

Figure 1. Tenacious under sail. Photo: Max

Length overall including bowsprit	65.00 metres
Length of hull overall	54.02 metres
Length on deck	49.85 metres
Maximum beam	10.60 metres
Depth amidships	6.60 metres
Air draught	39.52 metres
Displacement fully laden	713.2 tonnes
Total sail area	1217 metres^2

Table 1. Principal Dimensions

3 TOWING TANK TESTS

3.1 MODELS

Models were constructed of two potential hull designs at a scale of 1:25. The principal difference between the models was their underwater profile, see Figure 2.

A modest programme of towing tank tests had been conducted by the Wolfson Unit during the design of Lord Nelson. To assist with interpretation of the model results for this project, the existing model of Lord Nelson was re-tested with the new ship models to provide a known benchmark for comparison.

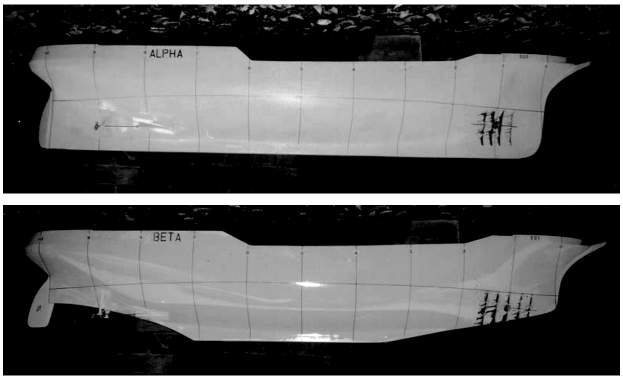

Figure 2. The two hull models for the new ship

3.2 TEST FACILITY

The tests were conducted in the tank at Southampton Institute. The tank is 61m metres long by 3.7m wide by 1.8m deep. It is equipped with a computer controlled wavemaker to generate regular waves or representative seastates.

3.3 TEST PROGRAMME

3.3 (a) Performance Under Power

Upright resistance tests were conducted in the design half load condition at 4 to 16 knots, somewhat greater than the anticipated service speed.

3.3 (b) Performance Under Sail

To obtain a force matrix for input to the velocity performance prediction (VPP) software, the models were tested at heel angles of 10, 15 and 20 degrees, at speeds of 7, 10 and 12 knots. In each case a range of leeway angles was tested to determine the sailing side force, and a range of rudder angles to determine the effect of helm on the centre of lateral resistance (CLR).

Standard Wolfson Unit procedures for these tests have been described by Claughton & Campbell [2].

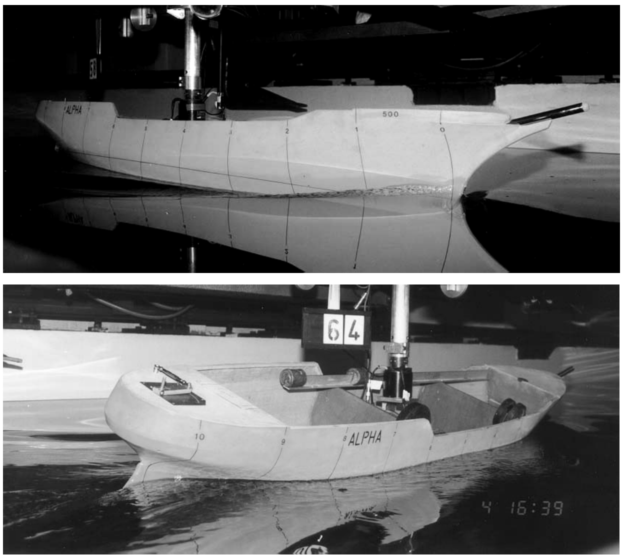

Figure 3. Tenacious model during heeled and yawed tests

3.3 (c) Seakeeping

With disabled crew, seakeeping was a prime design consideration. Tests were conducted with the vessel upright, and heeled and yawed in head seas. The test budget did not extend to tests in oblique seas in a seakeeping basin, but computer predictions were used to extend the results to other headings. The calculations were calibrated using model data obtained in regular head seas. This technique provided predictions of the motions, the ability of the crew to work and move about the ship, and seasickness incidence. These techniques were the subject of a paper by Campbell & Weynberg [3]

The model tests also provided information on the added resistance in waves, and the incidence of bow emergence and deck wetness in head seas.

3.3 (d) Roll Period

A slow natural roll period was a requirement for the ship, and the models were tested to quantify this. It is not possible to calculate the roll period accurately because it is highly dependent on the added inertia of water entrained around the hull as it rolls.

The two models, together with the model of Lord Nelson, were ballasted to model the displacement, centre of gravity and roll inertia calculated by the designers. They were rolled freely in calm water and the roll periods measured with a roll gyro.

4 WIND TUNNEL TESTS

4.1 MODEL

A model of the hull, deckhouses and rig was constructed at a scale of 1:30. The model rig included all spars and platforms, and the principal stays and shrouds. Care was taken to model the yard pivot and shroud geometry to ensure that the correct yard bracing angles could be achieved. Sails were manufactured by a sailmaker, using normal sailmaking techniques, with a cloth that would maintain the required sail shape at the wind speed used.

4.2 TEST FACILITY

The tests were conducted in the University no.1 wind tunnel, which has a working section 4.6m wide by 3.7m high. The model was mounted on a six component balance to provide a complete matrix of forces and moments.

4.3 OBJECTIVES

The following were seen as the principal objectives of the wind tunnel tests:

To obtain data for input to the velocity performance prediction (VPP) software, for a range of sail configurations.

To determine the longitudinal centre of effort to ensure good helm balance, and determine its sensitivity to sail combinations and sheeting.

Figure 4. Wind tunnel model with full sail set

To measure the basic hull and spar windage to assist powering predictions.

To highlight any potential interference between sails and other rig components, and examine sheet leads.

To enable the designer and crew to investigate the relative merits of alternative sail sets or sheeting variations.

4.4 TEST PROCEDURES

The wind tunnel dynamometer and test techniques were as used to investigate wind heeling moments for the development of sailing vessel stability standards, and have been described previously by the author [4] and [5]. They were subsequently developed further and the procedures were elaborated on by Claughton & Campbell [6].

5 PERFORMANCE UNDER POWER

5.1 MOTORING PERFORMANCE PREDICTIONS

The total resistance of the vessel was predicted using the towing tank hydrodynamic resistance data together with the wind tunnel aerodynamic resistance data for the model with bare poles. Because the wind tunnel model did not incorporate all of the standing and running rigging or the furled sails, an estimate was made of the additional resistance of the missing items. Information was obtained from the rig designers to assist with the estimates of the amount of cordage aloft.

A number of cases were considered, ranging from motoring in still air and calm water, to a gale force head wind and seas. For each case the total resistance was predicted and the Wolfson Unit's propeller design software was used to determine the optimum propeller parameters. The wide range of powering conditions, from motor sailing to motoring into a gale, present very different propeller requirements and Tenacious is fitted with a controllable pitch propeller to improve efficiency at the off design conditions.

5.2 FULL SCALE MOTORING PERFORMANCE

The predictions indicated a maximum speed of 11.5 knots in calm conditions, and this was achieved with a small margin on delivery trials. The correlation was considered to be very good.

In retrospect it is clear that the seakeeping tests were conducted at speeds which are not achievable in head winds. The windage of square rigged ships is very high, and their motoring speeds to windward are consequently low. The seakeeping tests in head seas were conducted at 9 knots and the data on added resistance in waves is unlikely to be representative of a strong head wind situation when, for example, the ship is motoring into a gale at 2 knots.

6 PERFORMANCE UNDER SAIL

6.1 SAILING PERFORMANCE PREDICTIONS

These predictions were made using the Wolfson Unit's own VPP software, WinDesign. It enables input of hydrodynamic data for the hull and rudder, aerodynamic data for the rig, windage, resistance due to heel, added resistance in waves and stability characteristics,

Sailing performance predictions were made following the tests, but for the purpose of this correlation exercise they have been revised to incorporate the as-built values for various parameters.

Since the tests, minor modifications to the sail plan have altered individual sail areas. It has been assumed that the lift and drag coefficients of the sails are principally dependent on sail shape, camber and interference rather than their areas. The sail coefficients derived from the wind tunnel tests have therefore been combined with the final sail areas to provide sail force input data for the VPP software.

The displacement and stability characteristics as determined by the inclining experiment have been used in place of the early design estimates, and a half load condition has been assumed.

Performance originally was predicted for all points of sailing, but limited operational data were available from the ship. The available operational data were concentrated in the heading range between 60 and 120 degrees of apparent wind angle. Square rigged ships tend to have limited ability to sail close to windward, and are more efficient on a broad reach than downwind, so this range is representative of normal sailing operations.

To segregate the data for clarity of comparison with operational data, a number of representative wind angles have been selected for presentation here. The data are presented as curves in Figures 5 to 7. The curves represent the predicted best ship speed and the associated heel angle in each case.

Figure 5 presents data for beating to windward with the normal working rig, which is about 80% of the total sail area, at an apparent wind angle of 60 degrees. Figure 6 presents data for beating to windward with two reduced sail plans. When beating with these reduced sail areas a greater apparent wind angle is more common, and 70 degrees has been selected for this comparison. The ‘reduced rig’ has a little over half the full sail area, and the other is a typical storm rig with the sail area reduced to 27%. Figure 7 presents data for a reaching situation with an apparent wind angle of 110 degrees, for all three sail plans.

The curves represent the best sail performance achieved through a progressive series of sail bracing and trimming adjustments in the wind tunnel. The test procedure involves trimming the sails while monitoring the driving and heeling forces in an attempt to achieve the maximum drive. This involves alterations to the sail sheeting, camber and twist. With a square rigged ship it also requires adjustments to the bracing angles and twist within the stack of square sails. These adjustments are made with the aid of electric sail winches, operated from the control room where the experimenter can view the displays of the force measurement system.

The sails are then progressively eased to reduce the heeling force while striving to maintain the maximum ratio of driving force to heeling force.

Sail trimming is highly sensitive and the wind tunnel offers a unique opportunity for crews to quantify the effects of their actions. When at sea, the variable environment tends to mask the effects of small adjustments to the trim, but in the wind tunnel the measurements quickly settle any debate over the most efficient way to trim the sails.

It has been the experience in most wind tunnel programmes that the optimum performance of a rig is obtained within a small range of sail settings. When operating off the optimum, relatively large adjustments have less effect on the overall performance.

6.2 FULL SCALE SAILING PERFORMANCE

Sailing performance data were noted by the captain on a number of occasions during the first year of operation. Sample data are presented in Figures 5 to 7 for comparison with the predictions. Inevitably the data exhibit scatter resulting from a range of factors such as differing loading conditions, combinations of sails set, and seastates.

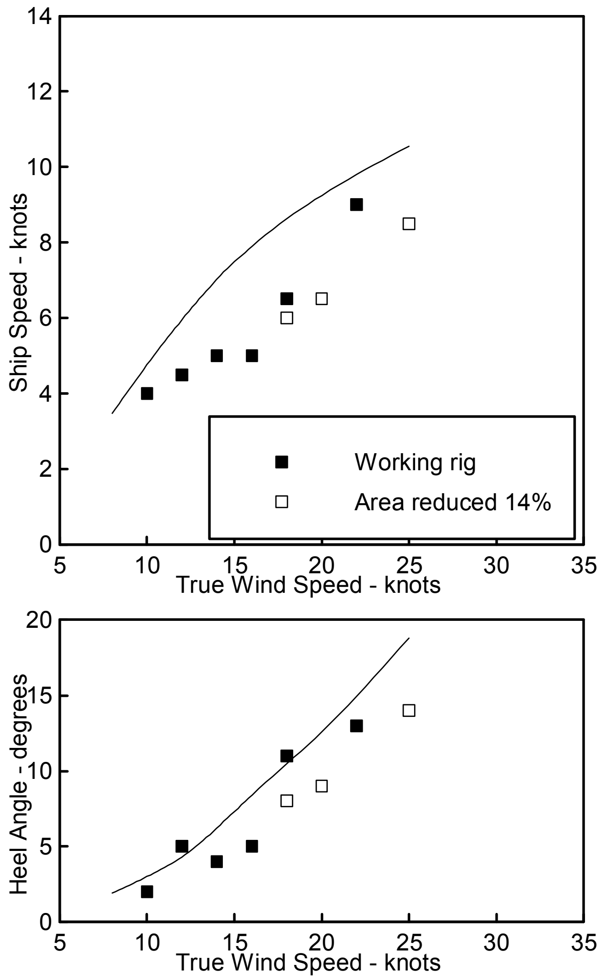

Figure 5. Comparison of predicted (curves) and observed upwind sailing performance with the working rig

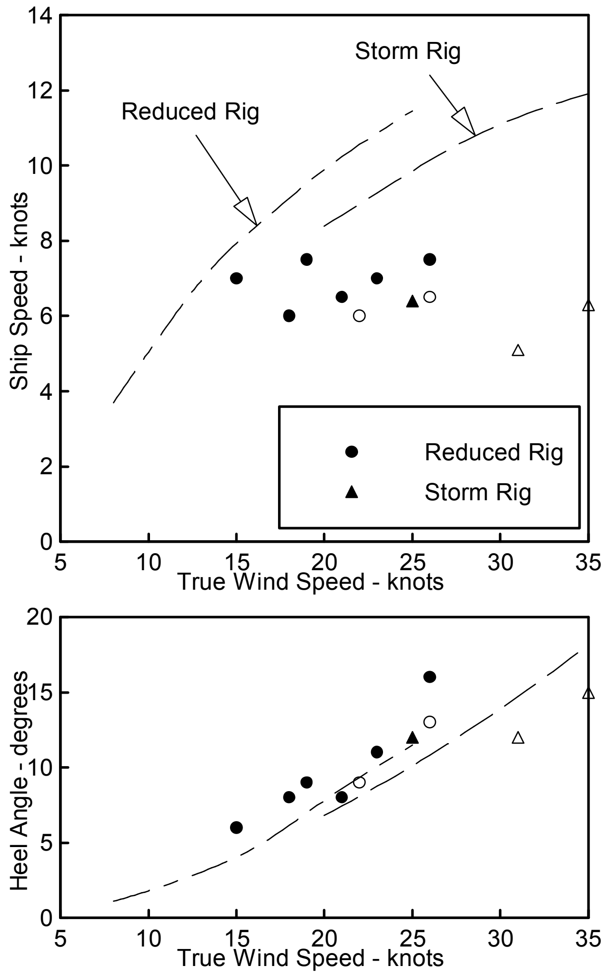

Figure 6. Comparison of predicted (curves) and observed upwind sailing performance with reduced rigs

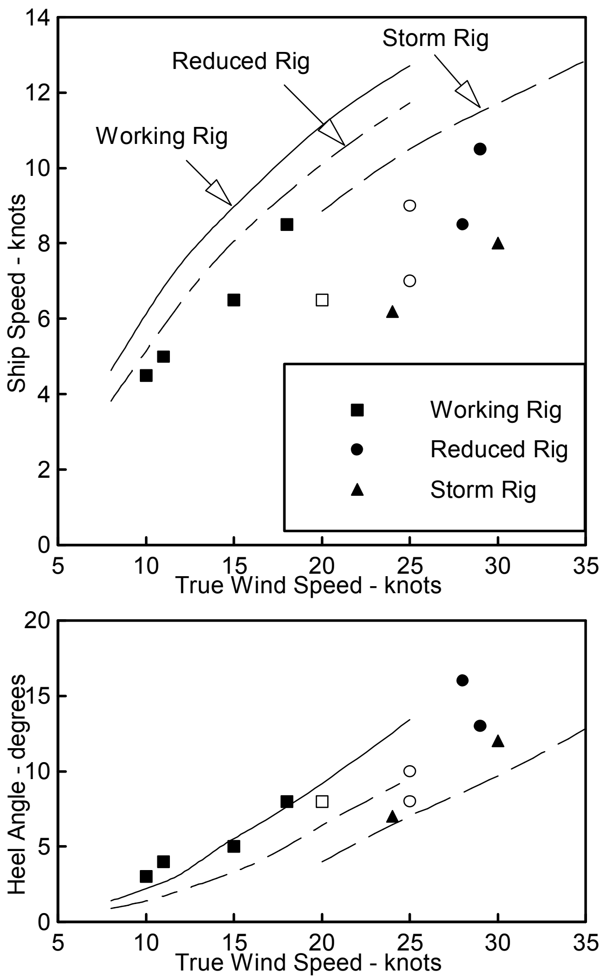

Figure 7. Comparison of predicted (curves) and observed reaching sailing performance

While the predicted curves are based on data at specific wind angles with fixed sail plans, the operational data represent a range of angles and combinations of sails set. Data have been selected to match as closely as possible the wind angles and sail configurations, but some allowance for variation was required in order that the limited amount of data could be incorporated. The apparent wind angles vary within +/- 10 degrees of those used for the predictions. The combinations of sails set varied, as did the total area, in comparison with those used for the predictions. Where the sail area set was less than 95% of that used for the predictions an open, rather than solid, symbol has been used on the graphs.

Inspection of the Figures reveals that the speeds achieved under sail have never exceeded those predicted. From the point of view of correlation this is encouraging, because the predictions represent the best possible performance.

On occasions the speeds compared well with the predictions but typically the ship's speed under sail is significantly lower than the predictions suggest. With the reduced rig cases illustrated the differences are particularly marked.

Discussions with the captain have revealed that the reasons for this apparent poor correlation are inherent in the way in which the ship is operated. The philosophy of the Trust is to conduct all activities at a speed which enables the slowest member of the crew to take an active part. This philosophy extends to all aspects of the operation so that, although the ship is required to follow a voyage timetable, the schedules are planned with adequate time allowances and voyages are relaxed. Sailing speed is not a priority therefore, and the sails may be set, for example, to maintain a comfortable heel angle rather than to press the ship to sail fast.

It is clear that, as wind speed increases, the difference between the predicted and observed speeds increases. This might be because the sailing performance moves down the list of priorities as wind speed increases, but may also be due to inaccurate modelling of the added resistance in waves in the VPP calculations. The predictions used the standard formulation contained within the VPP software, which is based on tests on a series of sailing yacht forms rather than the measured added resistance of the Tenacious hull. Yet another factor in higher wind speeds and seastates is the roll and pitch motion of the ship, which will have an adverse effect on the aerodynamic performance of the rig, but is not considered in the VPP predictions.

One might expect the sails on Tenacious to be eased beyond the best performance settings at high wind speeds in order to reduce heel to a comfortable angle, and thus reduce the speed below that predicted. The captain confirmed that he generally limits the sailing heel angle to 15 degrees for comfort. The heel angles recorded compare well with those predicted, suggesting that this was not a factor. It should be borne in mind however, that the rig windage will contribute a major component of the heeling moment at the headings considered, and sail setting will result in a smaller adjustment to the heel angle than would be the case for a high performance yacht.

In some cases the observed heel angles exceed those predicted. It is believed that in these cases the sails were over sheeted, or braced, generating greater heeling force and lower driving force than the optimum settings.

It is possible that the windage assumed was rather low, and this would have the effect of giving optimistic predictions of speed and heel angle.

Overall, this exercise indicates that the ship could be sailed faster much of the time, but this is not a racing yacht, or even a high performance cruising yacht, and crew ability, participation and enjoyment take a higher priority than speed.

6.3 HELM BALANCE

As a result of the tests, modest adjustments were made to the fore and aft distribution of the rig to refine the balance, which has proved to be good. The flexibility of sail plan enables some tuning of the longitudinal centre of effort, but typically the ship carries about 5 to 10 degrees of weather helm. The rudder extends the full depth of the keel and therefore has a large area, but the lift generated by a rudder in this situation is much less than with a spade rudder, and so this weather helm is not considered to be excessive.

7 MANOEUVRING TESTS

7.1 MODELS

The towing tank models were fitted with shafts, brackets, propellers, an electric motor, and radio control of the speed and helm.

7.2 TEST FACILITY

The tests were conducted on a large, sheltered outdoor lake in calm conditions. See Figure 8.

Figure 8. Dieudonné spiral trial on the lake

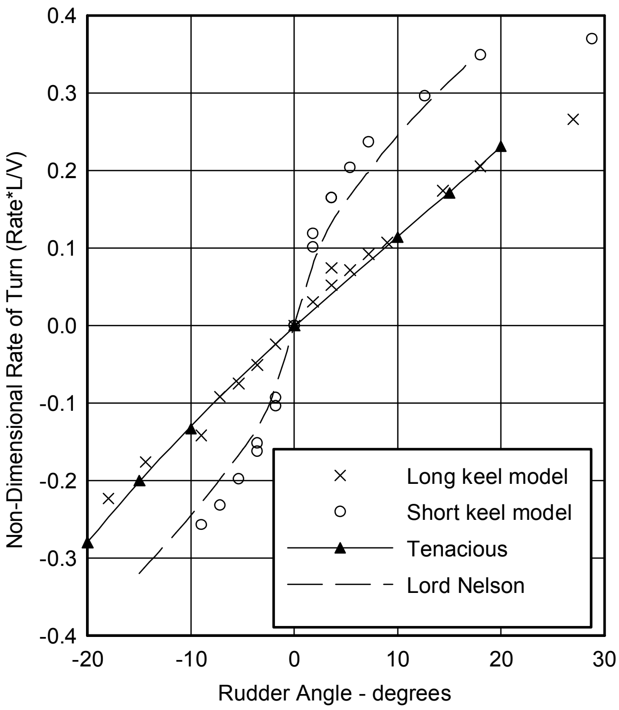

Figure 9. Measured rate of turn data for models and ships

7.3 OBJECTIVES & TESTS

One of the specified ship requirements was to have a high level of directional stability to facilitate control of the helm by handicapped and novice crew members. Dieudonné spiral manoeuvres were undertaken to determine the relative directional stability of the alternative hull forms.

7.4 TEST RESULTS

The model test data are presented in Figure 9 in terms of the rates of turn for a range of rudder angles. The rates are rendered non-dimensional by multiplying by waterline length and dividing by the speed. There is a very clear difference in the data for the short and long keel models. For the latter the data are almost linear, and indicate very high directional stability. The shorter keel model demonstrated high rates of turn, even at low rudder angles, and the data lie on a curve which is characteristic of low directional stability. For a vessel which is directionally unstable, the data would reveal hysteresis, with the possibility of turning against the applied rudder at small helm angles.

The rudder performance may be higher when situated behind the skeg on the short keel model, compared with its location behind the full length keel, but the difference in the rates of turn is believed to be dominated by the hull profile shapes.

7.5 FULL SCALE PERFORMANCE

The captain of Tenacious argued strongly in favour of the long keel, and is very pleased with the result. He reported that the ship holds a course with little attention from the helm and ‘is a delight to steer’. The ship has very high directional stability at the expense of manoeuvrability, and to assist in the latter a bow thruster was incorporated. The low rates of turn have an impact on the time taken and ease of tacking the ship, and it is notably slower in this manoeuvre than Lord Nelson.

The author was granted an opportunity in April 2002 to conduct some brief manoeuvring trials on Tenacious, in the Solent at the start of a scheduled voyage. The results are presented with the model data and demonstrate excellent correlation despite being conducted in less than ideal conditions with a wind of 12 knots. Because of the conditions, and very limited time available for the trials, measurements at small rudder angles were not possible, but the data confirm the linear relationship of turning rate with rudder angle.

Lord Nelson is known to have low directional stability, and good manoeuvrability with high rates of turn. These characteristics are beneficial to manoeuvring at close quarters and tacking, but can lead to course keeping difficulties for some novice crew members. The directional stability was measured at full scale with Dieudonné spiral trials when the ship was commissioned, and the data are presented for comparison. The similarity with the short keel model is striking.

8 SEAKEEPING

The seakeeping tests and computer predictions formed a significant proportion of the Wolfson Unit's input at the design stage, and full scale motion monitoring is a service offered by the Unit. Good correlation has been obtained in model and full scale programmes on motor vessels, but full scale monitoring of the seakeeping has not been conducted on Tenacious.

The captain has reported that he has been impressed with the motions and seakeeping generally, and the deep narrow forefoot eliminates slamming, but no quantitative data are available.

It has been noted that, when beating in rough conditions, large seas occasionally wet the main deck just aft of the forecastle. This was not predicted from the model tests because, although they addressed the upright motoring case and the heeled and yawed sailing case, tests in the towing tank are restricted to head seas. When beating to windward it is most likely that the waves will be closer to beam seas than head seas, with the ship's forward speed producing wave encounters from, say, 70 degrees off the bow.

9 ROLL PERIOD

The roll period is dependent on the metacentric height, GM, the radius of gyration, k, and the added inertia of water entrained around the hull. The added inertia may be considered as a factor, known as the roll constant, which is applied to the radius of gyration.

The roll period, T, may be expressed as:

$$T = 2\pi kC/(g\ GM)^{1/2}$$

From the measured roll period the roll constant, C, may be derived if the roll radius of gyration is known. For the ship the roll inertia, and the hence radius of gyration, may be calculated from the usual breakdown of weights in the designer's weight estimate. For the model it is measured by careful swinging and timing in the laboratory.

	GM m	Radius of Gyration k m	Model Roll Period T s	Ship Roll Period T s	Derived Roll Constant C
Long keel	0.84	5.11	13.6		1.22
Tenacious	0.90	5.10		12	1.11
Short keel	0.80	5.11	11.8		1.03
Lord Nelson	1.41	4.56	8.8		1.14
Lord Nelson	1.41	4.56		9	1.17

Table 2. Measured roll periods for the models and ships

Following the tests it was clear that the proposed design would have a slower roll motion than Lord Nelson, but it was noted that the derived roll constants for the three models were significantly different. They ranged from 1.03 for the short keel model to 1.22 for the long keel model. This implied a much greater amount of water entrained by the long keel form, as might be expected.

With the model of Lord Nelson a constant of 1.14 was derived. This came as a surprise since the hull form was similar to that of the short keel model, and one might expect a similar constant.

The captain of Tenacious has estimated the natural roll period of the ship in service to be about 12 seconds. This suggests rather poor correlation with the model measurement. It is a difficult value to estimate because ships roll at the frequency of the waves exciting them, albeit with greater amplitude at their natural roll, or resonant, frequency.

The same captain estimated the natural roll period of Lord Nelson to be about 8 seconds and subsequently conducted a forced roll test on the ship in port. These ships are heavily damped in roll, and difficulty was experienced in obtaining sufficient roll motion. The accuracy of the resulting period of 9 seconds therefore is not known, but it correlates very well with the model measurement, and suggests that estimates made from motions in service might under predict the value.

There are a number of possible reasons for the poor correlation for Tenacious. The natural roll period of the ship may not have been estimated correctly and, for the reasons given above, this is quite likely to be the case.

The calculated radius of gyration may have been incorrect, in which case the model was ballasted to a radius of gyration that did not represent the true full scale value. Whilst weight estimates are frequently inaccurate, the displacement of Tenacious as built corresponded to the design displacement and so this is not likely to be the source of the discrepancy. The stability as inclined, and the ballast arrangement, differed a little form the design values, and have been taken into account in the tabulated data.

The model may not have been ballasted accurately. It is straightforward to obtain the correct weight and centre of gravity, but notoriously difficult to measure the inertia and radius of gyration to a high level of accuracy, even in the laboratory. The measurement requires suspension of the model in air so as to enable a pure roll motion in the absence of friction. Test establishments recognise this as a common source of discrepancies in model preparation. It appears that the result for the short keel model may have been inaccurate, because the derived roll constant implies very little added inertia.

No attempt has been made to verify the full scale roll period of Tenacious, so the level of correlation is uncertain.

10 CONCLUSIONS

In general the evidence from the ship has been that the predictions based on model test data were reliable.

Excellent correlation was found between model and full scale performance in terms of the calm water powering and manoeuvring.

In this brief study of the sailing performance the heel angles correlated well but the speeds achieved were generally less than predicted. It is believed that the ship is not sailed to its optimum performance, but it is possible that some of the assumptions made in the predictions were optimistic.

The natural roll period estimated by the captain was less than predicted, but the accuracy of this estimate is not known. The measured roll period of Lord Nelson correlated well with model data.

Where this study was unable to obtain good correlation between model and full scale, there was a lack of accurate measured data from the ship. To improve on this situation would require a far more rigorous programme of full scale trials, but unfortunately there are no plans to conduct such work on this vessel.

11 ACKNOWLEDGEMENTS

The author is very grateful for the assistance provided by the captain and crew of Tenacious, and the staff of the Jubilee Sailing Trust, in providing data for this correlation exercise and the opportunity to take part in a short voyage to witness the performance of the ship.

Thanks are due to Tony Castro for permitting presentation of data relating to the design of Tenacious, and to Colin Mudie for permission to include manoeuvring data for Lord Nelson.

The assistance of Andy Bruce was very welcome in revising the sailing performance predictions.

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