WIND TUNNEL TESTS ON SCHOONER RIGS AND THEIR USE IN PERFORMANCE PREDICTION BY VPP CALCULATIONS

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HISTORICAL BACKGROUND

A tour around the maritime museums of the world will reveal the rich history of Schooner rigs used to propel commercial sailing vessels. Just a few examples are; the Schooners built in Dartmouth in the UK to ply the coal and fruit trade to the Mediterranean; those that sailed out of Paimpol in Brittany to fish off Iceland; and others that sailed from East coast ports in the USA to fish off the Grand Banks. It was clearly a universally successful working rig that also found favour in cruising and racing yachts, with America winning a race around the Isle of Wight almost 150 years ago to take the "America's Cup" to the New York Yacht Club.

In recent years a number of devotees have kept the Schooner rig alive and well through restoration, re-build and new-build projects. This paper describes tests conducted with wind tunnel models with the aim of continuing the development of the Schooner rig.

TECHNICAL BACKGROUND

It can be difficult to fit all the required sail area on to a single mast for a large yacht. Small sloop-rigged yachts can be scaled up to larger sizes but to have the same scale performance, according to Froude scaling, the wind speed should increase with the square root of scale. This is less likely to occur in practice, since for example a large and small yacht sailing together operate in the same wind speed, except for the increase with mast height due to the wind gradient. It can therefore be desirable to increase the sail area of a large yacht relative to that of a small yacht.

Two-masted Schooners and Ketches provide a means to increase sail area by giving an overall trapezoidal shape to the rig compared to the triangular shape of a Sloop. Both the overall and centre of effort heights of a trapezoidal rig will also be lower than that of a triangular rig of the same area. A lower overall rig height will reduce the aspect ratio of the rig with an associated reduction in the aerodynamic efficiency of the rig through the increased induced drag due to lift. The lower centre of effort height will offset this, in part, with a consequential reduction in the heeling moment, which may give performance advantages in some conditions.

There are a wide variety of Schooner sail plans involving combinations of sails set flying from or attached to the mast, which makes selection of the sail plan interesting.

RIG DESIGN PROBLEMS

The wind tunnel tests described in this paper involved the study of the two-masted classic Schooner rig shown in Figure 1. The features of the "classic rig" may be listed as follows:

A higher mainmast than foremast.
A bowsprit, from which the outer jib is set.
Two other similar sized headsails – an inner jib and staysail.
A foresail, with a sail plan to fill most of the between mast area.
A Bermudan mainsail set on a long boom.

Design problems for this type of schooner rig include:

Optimisation of the headsail arrangements within the fore-triangle to avoid interference problems between the sails and to maximise their performance.
Optimisation of the foresail, with sail options being a gaff foresail with topsail, a wishbone topsail or a modern fully battened large roach foresail.
Design of off-wind sails to be flown between the masts, without undue interference with the foremast.
Consideration of reefed sail configurations to maintain balance with the hull.

The "modern" Schooner rig, which is shown in Figure 2, was tested to investigate some of these design problems.

WIND TUNNEL TEST ARRANGEMENTS

The Wolfson Unit conducted the tests in the wind tunnel at the University Southampton. The low-speed test section is 4.6 metre wide by 3.7 metre high. A complete model consisting of hull, mast rigging and sails was mounted on a six-component dynamometer, which is fitted under the floor of the wind tunnel.

The wind tunnel arrangement enables the sail forces to be measured without any reference to the performance of the yacht, whereas when sailing the sail forces cannot be measured directly and the effect of any changes can only be assessed from changes in the velocity of the boat. The wind tunnel is operated at a constant speed, thus eliminating the effect of fluctuations in wind speed that make data gathering from full scale trials difficult. The requirement to trim sails to suit different wind speeds has to be simulated by the experimenter since the rig is firmly attached to the dynamometer and does not alter in heel during a set of runs.

Further details of the experimental setup are described in reference 2.

THE SCHOONER RIGS TESTED

To aid the development of Schooner rigs for the design of particular yachts a number of wind tunnel tests have been conducted at the University of Southampton. The data presented in this paper was derived from tests for two yachts of slightly different size but sufficiently similar to be represented by the same model. The data have been scaled from the model test results by a common factor of 1:25 and the size difference between the yachts' rigs was treated subsequently by applying additional scale factors.

The sail plans are shown in photographs with examples of the full up-wind and off-wind sails used in the tests shown in Figure 1 for the classic rig and Figure 2 for the modern rig. Because the tests were related to different designs, they were conducted in different test sessions spaced several months apart, with the model refurbished and reinstalled into the wind tunnel for the tests on the modern rig.

The classic upwind sail configuration consisted of three headsails, a gaff foresail with fore topsail and a Bermudan mainsail, with a total sail area of 1225 m^2. The modern upwind sail configuration consisted of two headsails, a fully battened large roach foresail and a fully battened mainsail, with a total sail area of 1146 m^2. The smaller sail area of the modern rig was principally due to differences in the mainsail area and headsail areas. The height of the main mast above the datum water line was 47.9 m for both the classic and modern rigs.

The modern rig is designed to produce improved performance by taking advantage of modern sail materials and sail handling systems.

The classic, or nearly classic, off-wind sail configuration consisted of the upwind rig with the outer jib replaced by an asymmetric spinnaker and the foretopsail replaced by a fisherman sail, with a total sail area of 2046 m^2. The modern off-wind sail configuration consisted of the yankee jib replaced by an asymmetric spinnaker and the foresail replaced by an asymmetric main gennaker, with a total sail area of 2314 m^2.

The modern off-wind rig is designed to produce improved performance by taking advantage of modern asymmetric sail shapes to increase the sail area.

SAIL SHEETING CONSIDERATIONS

The model tests in the wind tunnel provide the opportunity to study the sheet leads, for positioning deck fittings, and sail interactions, between themselves and with the standing and running rigging. The three headsails in the classic rig overlapped so variations in relative tack positions and sizes were tested to determine combinations that avoided interference between the sails. The foresail is an interesting sail to set because it is between the headsails and the mainsail and there are various combinations of boom angle and sail twist that can be used. It was found that to some extent the foresail sheeting had rather less effect on the driving force and heeling moment than the sheet adjustments to the headsails and mainsail. Sheeting information such as this could be used to help the crew operate the yacht and the designer optimise the winch requirements.

The fisherman and the main gennaker can both interact with the foremast rigging, furthermore the gennaker should be set to avoid chafe with the foremast runners and the lower triatic stay. The interaction depended on the sail sheeting and its optimisation at different apparent wind angles. At apparent wind angles of greater than 90 degrees the interactions with the rigging restricted the extent to which the gennaker sheet could be eased and in some conditions this limited the maximum driving force that could be achieved. At apparent wind angles of greater than 135 degrees significant blanketing effects occurred between the sails, which would restrict performance and the extent to which the yacht could be sailed downwind.

All the data points measured, including those presented in this paper, followed trimming of the sails to optimise the driving force for the required heeling moment. Initially, the maximum driving force was sought irrespective of the heeling moment, then the heeling moment was reduced in stages and the highest driving sought for each condition.

DATA FROM TESTS

The test data presented in this paper are for particular up-wind and off-wind sail combinations for the two Schooner rigs. They are representative of much larger sets of data for various sail combinations that were tested to aid the rig development for the yachts.

Corrections were applied to the data for zero drift during a set of runs, which could typically involve 15 minutes between starting and stopping the wind. Wall boundary and wake blockage corrections were also applied as described in references 2 and 3. The forces and moments were measured on the body axes of the model, which was set a zero leeway angle on the dynamometer. These driving and heeling forces were transformed in the analysis to the apparent wind axis and normalised by the sail area and dynamic wind pressure to produce the lift and drag coefficients.

AERODYNAMIC CHARACTERISTICS REVEALLED BY THE TESTS

Driving forces and heeling moments

The driving forces and heeling moments affect directly the performance of a yacht. When the heeling moment is in balance with the righting moment the driving force, corrected for heel angle, must be in balance with the drag and this will determine the speed of the yacht. The Velocity Performance Program (VPP) iterates to the equilibrium of these aerodynamic forces and moments with the hydrodynamic forces and hydrostatic moments. It is, however, clear that if, at a particular apparent wind angle and heeling moment, the driving force from one combination of sails is greater than from another then the speed of the yacht will also be greater.

The curved lines shown on Figure 2 are calculated from values fitted to the lift coefficient, drag coefficients and centre of effort height, using the same algorithm as is in the VPP. It can be seen that a reasonable fit was achieved to all the test data across the full range of heeling moments. It should be borne in mind when studying the data in Figure 2 that the reduction in heeling moment at unit wind pressure represents those adjustments in the sheeting of the sails that would be made when sailing in increasing wind strengths to control the heel angle. The heeling moment may increase due to the increase in wind pressure.

It can be seen from the data that at apparent wind angles of 25 and 30 degrees the VPP fit and the data tend to a maximum value for the driving force that would not increase with a further increase in heeling moment. The maximum performance of the rig at these angles is limited by its aspect ratio and the influence of this on the increase in induced drag due to lift. At wider apparent wind angles the induced drag has less effect on the driving force and the VPP fitted curves show an upward trend at the maximum heeling moment. The maximum driving force at apparent wind angles greater than 36 degrees is limited by the maximum lift that can be developed by the rig.

Comparison of the data from the tests on the two rigs indicate that at apparent wind angles of 25 and 30 degrees the modern rig produced significantly higher driving forces than the classic rig. Thus the modern rig would have better windward performance despite having a smaller sail area than the classic rig. At an apparent wind angle of 60 degrees it can be seen that the classic rig produced higher driving forces than the modern rig, probably due to its larger sail area.

Windage

The total windage of the hull, deck, mast and rigging was measured by removing the sails from the model. The windage forces were subtracted from the total forces obtained with the sails to produce the residual sail coefficients. The windage forces were then transformed to lift and drag coefficients using the upwind sail area as the reference area. This enables straightforward comparison of the windage coefficients with the sail coefficients.

If wind tunnel test data is used in a direct manner to compare different sail then this should be done on the basis of the total sail forces or moments. If, however, the wind tunnel data is used to derive coefficients for use in Velocity Performance Predictions (VPPs) then the windage should be input as a separate component to the sail forces. This ensures that the VPP reefing routine operates properly, otherwise the VPP will invoke the reef function at too low a wind speed because it will incorrectly reduce the windage area with the sail area.

Since the windage forces were subtracted from the total forces in the derivation of the sail coefficients it is necessary to use the same centre of effort for the windage as that derived from the heeling moment and heeling force for the rig with sails.

The windage lift and drag coefficients are shown in Figure 6 together with the shape functions used in the WinDesign VPP for the variation of windage with apparent wind angles. It can be seen that the shape functions do not match the test data over the full range of apparent wind angles. Since windage is most significant in affecting windward sailing performance the windage areas and coefficients were adjust in the VPP to match the driving forces to those from the tests over the apparent wind angle range of 25 to 45 degrees. This can be seen from Figure 5, which contains the measured windage forces.

Variation of drag with lift

When the sail forces are transformed from the body to wind axes the data from tests at different apparent wind angles tend to collapse as can be seen in Figure 3. This indicates that the aerodynamic characteristics of the rigs are determined by their overall shape, planform and aspect ratio, despite the changes in sheeting required as the apparent wind angle is increased and despite the associated changes in the relative positions of the sails.

Comparison of the data from the tests on the two rigs indicate that the modern rig produced significantly less drag at the higher values of lift than the classic rig. This is indicated by the dotted lines shown in Figure 3, which are values fitted to give an effective rig height, He. It can be seen that this is higher for the modern rig.

In the Hazen aerodynamic model, reference 4, there are two components of drag that are proportional to the square of lift, the induced drag due to lift and a component of viscous drag which also varies with lift. This viscous component is a smaller part of the total drag. In reference 2 it was shown that the Hazen model could be fitted to wind tunnel data from tests on a Bermudan sloop rig. The data from the Schooner rig tests had, however, slightly different characteristics, with a tendency for a slight curve in the variation of drag coefficient with the square of lift coefficient. This tendency could be attributed to the effect of twist on induced drag, as the sails were eased to reduce the heeling moment.

The data fit for the VPP was obtained by first fitting a curve through the variation of lift with apparent wind angle, as shown in Figure 4, and then obtaining the associated maximum drag coefficient from Figure 3. The effective rig height is used to obtain the reduction of drag with lift as the sails were eased. At zero lift, the intercept of the line associated with the effective rig height was not zero drag, despite having subtracted the windage forces from the data. This was partly due to the fit of the line to the curve of data, as described above. Caution must therefore be taken in the interpretation of the values of effective rig heights of 49m and 51m, for the classic and modern rigs respectively, compared to the geometric rig height of 47.9m.

Lift coefficients

The variation of lift coefficients with apparent wind angles for the upwind rigs is shown in Figure 4 together with a curve fitted through the values associated with the maximum driving force for input to the VPP. It can be seen that the modern rig tended to produce slightly higher values of lift coefficient than the classic rig.

The variation of lift coefficients with apparent wind angles for the off-wind rigs is shown in Figure 8. These show a maximum value at an apparent wind angle of 60 degrees, with a progressive reduction towards zero lift at an apparent wind angle of 150 degrees. At an apparent wind angle of 90 degrees all of the lift contributes to the driving force. It can be seen from the results of the VPP calculations, given in Table 1, that this angle is only reached when sailing in the optimum downwind Vmg condition in a true wind speed of 14 knots.

Comparison of the lift coefficients for the classic and modern off-wind rigs shows that the modern rig produces higher values. This may be attributed to the increased camber of the main gennaker compared to that in the foresail and fisherman. The combination of increased lift coefficient and increased sail area of the modern off-wind rig significantly increase the driving force.

Drag coefficients

The variation of drag coefficients with apparent wind angles for the off-wind rigs is shown in Figure 9. At apparent wind angles of less than 90 degrees the drag acts to reduce the driving force so low values for a given value of lift are desirable.

Comparison of the drag coefficients for the classic and modern off-wind rigs shows somewhat different shaped data fits. The higher drag coefficients that the modern off-wind rig produces at an apparent wind angle of 75 degrees are associated with the higher lift coefficients. It is interesting to note that the drag coefficients from both rigs are similar at an apparent wind angle of 120 degrees, where the drag contributes to the driving force.

Centre of effort height variations

Figure 7 shows the variation of the centre of effort height with the heeling force coefficient (Cy) for the upwind rigs. Both the classic and modern rigs showed a clear trend of reducing height with reducing heeling force. This is attributable to two factors:

Firstly the heeling moment is strongly affected by the sheeting of the main sail, which has the highest centre of area of all the sails. As the main sheet is eased so its contribution to total aerodynamic force is reduced and the overall centre of effort height tends towards the lower centre of area of the sail plan of the foremast;

Secondly the twist in both the mainsail and the foresail increased as their sheets were eased to reduce the heeling moment. The twist could be controlled by the relative tension in twin sheets, led to either side of the centreline, but allowing twist was found to optimise the driving force at reduced values of heeling moment coefficients.

The WinDesign VPP has a linear reduction of centre of effort height with the flat function, which is used in the program to reduce the lift coefficient to control the heel angle. The factor in the VPP for the rate of reduction was determined from the test data.

Another trend that is particularly apparent in the data from the modern rig is the reduction in centre of effort height with apparent wind angle. In the version of WinDesign used in the VPP analysis for this paper there was no function to simulate this trend but will be incorporated in future versions. This increased the difficulty of the task of fitting values of lift and drag coefficients to give a match to the driving force and heeling moment data across the range of apparent wind angles from 25 to 60 degrees.

VPP CALCULATIONS

Program and inputs

Performance calculations were made using the WinDesign VPP, which is described in reference 1. Sail coefficients are input to this program as a table of apparent wind angles with maximum lift coefficients and the associated drag coefficient, together with the reference sail area, centre of effort height and effective rig height. This height is used to obtain the reduction of drag with lift when the VPP applies the flattening function to control the heel angle of the yacht.

Data fits

Although the table of inputs to the VPP for sail coefficients appears simple, care must be taken to ensure that there are fair curves through the variation lift and drag coefficients with apparent wind angle, because the VPP will interpolate between the tabulated values. The input lift and drag coefficient must also represent the experimental driving forces and heeling moments from which they were derived.

The data fits were derived by plotting them on the charts in the spreadsheets that were used to analyse the data. The driving forces and heeling moments were recalculated, using the same algorithm that is in the VPP, from the fitted lift and drag coefficients and the selected centre of effort and effective rig heights. The process involves manual manipulation of the data to obtain the best fit over the full range of test conditions.

The results from the VPP calculations are given in Table 1.

Up-wind performance

The VPP predictions for the modern rig showed the interesting result that the optimum speed made good to windward (Vmg) occurred at an apparent wind angle of between 24 and 25 degrees for a wide range of true wind speeds from 5 to 16 knots. The true wind angle, and hence the tacking angle for the yacht, decreased from 52 degrees in 5 knots of wind to 47 degrees in 16 knots of wind. The VPP indicated that the yacht should reduce sail in wind speeds above 16 knots and other wind tunnel tests were conducted to optimise the reduce sail configurations for the rig.

It is interesting to note that the flat function values given in Table 1 for the optimum up-wind Vmg sailing condition have values of less than 1.0 at all true wind speeds from 5 knots and higher. This indicates that the optimum performance from the rig is achieved without sheeting the sails as hard as could be achieved in the wind tunnel.

Off-wind performance

Unlike the prediction of optimum up-wind conditions, there was a considerable variation with wind speed for the apparent wind angles for optimum speed made good down wind, although the optimum true wind angle only varied from 142 degrees in 5 knots of true wind to 155 degrees in 16 knots. The associated apparent wind angles varied from 47 to 106 degrees. These predictions indicate that provided the yacht is sailed at an angle for optimum downwind Vmg speed then the blanketing and interference effects between the sails, discussed earlier, should be avoided. It can, however, be seen that the sails were not tested to the lowest apparent wind angle predicted by the VPP and it may not be possible to set the sails at these angles. Other sail combinations were tested for these conditions

HEEL CORRECTIONS

It can be seen from the photographs of the tests that they were conducted with the model upright. This simplifies the analysis of the data since the sail coefficients input to the VPP are those in the plane normal to the mast, which is the measurement plane for the upright condition. Algorithms within the VPP, based on reference 5, calculate the driving force and heeling moment for the heeled yacht. Essentially there is a reduction in the driving force with heel angle, as shown in reference 2, that may be considered to be related to the reduction in apparent wind angle in the heeled plane from that in the horizontal plane.

Tests have been conducted with a model upright and heeled, with the same sail configuration, and the data were corrected to produce lift and drag coefficients in the plane normal to the mast. The corrections used the same algorithms as those in the VPP with due account taken of the horizontal measurement plane for the driving and heeling forces. In general there was good correlation between the data from the upright and heeled tests, subject to some variability in reproducing the sheeting conditions in both tests.

CONCLUSIONS

The tests produced consistent data with clear differences between the classic and modern rigs. The results enabled informed decisions to be made regarding the sail configurations for the designs under consideration. Sail coefficients were fitted to the data such that they matched the measured forces and could be input to a VPP. This program then produced reliable predictions of the potential performance of the different yacht designs and enabled the relationship between their stability and sail area to be assessed.

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		True wind speed (V_t) - knots										
		5	**6**	**7**	**8**	**9**	**10**	**12**	**14**	**16**	**20**	**25**
Optimum up-wind V_{mg} sailing condition												
β_t	degrees	52.4	51.5	50.6	49.8	49.0	48.3	47.5	47.3	47.4	47.4	48.2
B_a	degrees	24.0	24.0	24.1	24.3	24.5	24.8	25.5	26.3	27.4	29.1	31.6
V_s	knots	5.81	6.69	7.42	8.01	8.48	8.85	9.43	9.85	10.17	10.46	10.7
V_{mg}	knots	3.54	4.17	4.71	5.17	5.56	5.89	6.37	6.68	6.88	7.09	7.14
heel	degrees	6.2	8.3	10.4	12.5	14.4	16.1	18.9	21.3	22.2	24.4	24.8
reef		1	1	1	1	1	1	1	1	0.95	0.91	0.74
flat		0.85	0.82	0.78	0.74	0.7	0.66	0.58	0.5	0.49	0.41	0.49
Beam reaching with true wind angle B_t = 90 degrees												
β_a	degrees	29.7	30.9	32.3	33.9	35.8	37.7	41.3	44.8	47.9	53.1	58.0
V_s	knots	8.66	9.8	10.71	11.36	11.79	12.12	12.59	12.93	13.21	13.68	14.11
heel		8.6	11.6	14.2	16.4	18.1	19.5	21.7	22.6	22.7	23.3	24.2
reef		1	1	1	1	1	1	1	0.96	0.89	0.79	0.7
flat		1	1	0.97	0.92	0.88	0.84	0.76	0.73	0.76	0.8	0.83
Optimum down-wind V_{mg} sailing condition												
β_t	degrees	142.5	142.9	143.3	143.3	144.1	145.5	149.1	152.6	154.6	155.1	168.5
β_a	degrees	46.9	48.4	50.7	53.3	57.2	62.8	77.7	93.6	105.9	118.6	155.1
V_s	knots	6.81	7.99	9.02	9.96	10.67	11.13	11.63	12.02	12.5	13.55	13.76
V_{mg}	knots	5.4	6.37	7.23	7.98	8.64	9.17	9.98	10.68	11.29	12.28	13.48
heel	degrees	3.1	4	4.8	5.7	5.9	5.5	4.2	3.3	2.8	3.3	2.7
reef		1	1	1	1	1	1	1	1	1	1	1
flat		1	1	1	1	1	1	1	1	1	1	1

Table 1. Results from VPP calculations with the modern rig