MODEL TEST PREDICTIONS AND FULL SCALE MEASUREMENTS: BEWARE!

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Summary

This is a tale of caution: When it comes to scale model tests and full scale measurements, make sure you are comparing apples with apples.

The reconstruction of *Jewel of Muscat*, a 55 tonne, 9th century ship, was successfully sailed from Oman to Singapore, traveling approximately 3600 nautical miles. Performance predictions based on towing tank tests of a scale model did not correspond even closely with performance on the voyage. Several possible reasons are investigated.

List of symbols

AWA	Apparent wind angle (degrees)
AWS	Apparent wind speed (knots)
JoM	Jewel of Muscat
TWA	True wind angle (degrees)
TWS	True wind speed (knots)
kn	knot
kN	kiloNewton (force)
R_t	Total resistance (kiloNewtons)
V_b	Vessel speed (knots)
VPP	Velocity Prediction Program

1. Introduction

The 9th-century Belitung shipwreck, discovered in 1998 off the island of Belitung, Indonesia, was the first sewn-plank vessel discovered in the greater Indian Ocean and provided the opportunity to recreate a vessel based on the remains of the shipwreck.

A design was created, a scale model of which was tested in a towing tank by the University of Southampton (Wolfson Unit, 2008). Some modifications in hull form and rig were made as a result. The 18m, 55 tonne vessel was built on a beach in Oman, using (in most cases) 9th-century methods. The ship, which took a year to build, successfully sailed from Oman to Singapore, over a period of four months, with 66 days at sea, traveling approximately 3600 nautical miles. There were several stopovers, including a vessel haulout at Cochin.

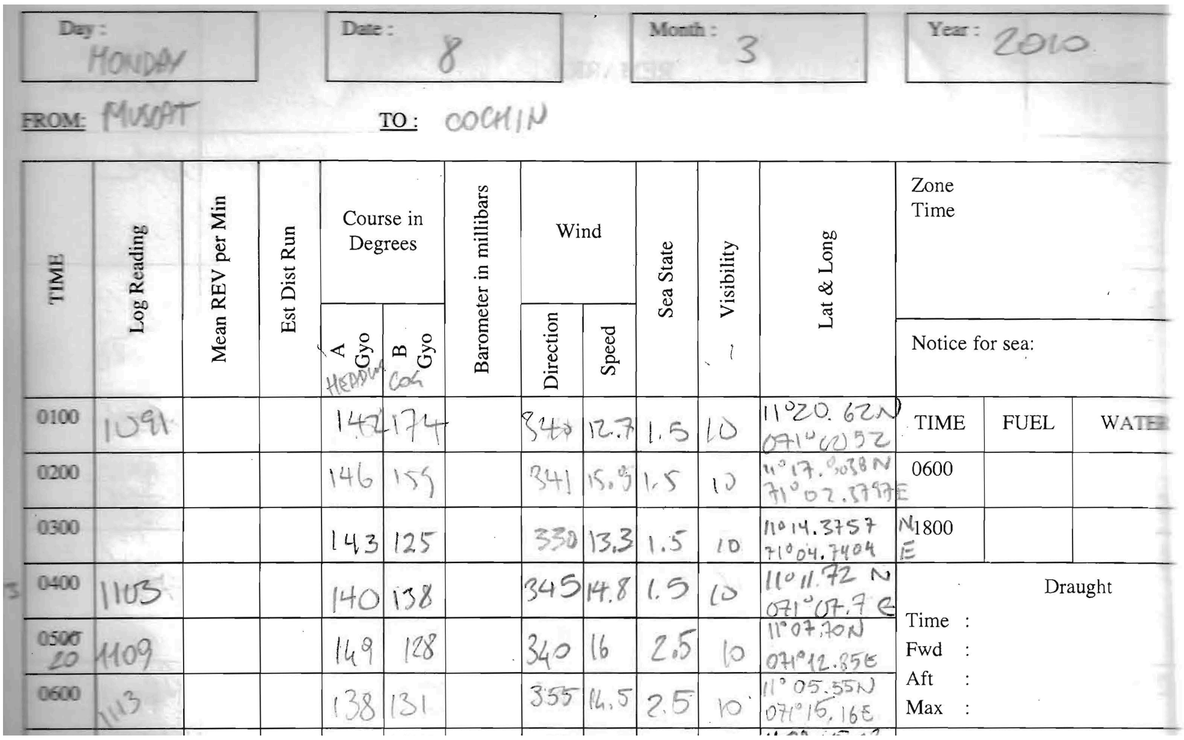
Comparison of performance predictions made from the model tests and the ship's log revealed significant discrepancies. The measured vessel speeds were much lower than predicted, and the leeway angles were an order of magnitude higher. Unravelling the likely causes of these discrepancies followed the t-shirt definition of engineering: precision guesswork based on unreliable data using inadequate tools…

Figure 1 Jewel of Muscat under sail   A. Ghidoni

Figure 2 weather encountered during the voyage *A Ghidoni*

2. Analysis of ship's log

The ship's log for the voyages from Muscat to Singapore contains entries (typically hourly) of position, distance run, course, heading, wind speed and direction, sea state and visibility. There are also intermittent comments. A sample is shown in Figure 3.



Day : MONDAY Date : 8 Month : 3 Year : 2010

FROM: MUSCAT TO : COCHIN

TIME	Log Reading	Mean REV per Min	Est Dist Run	Course in Degrees: A Gyo (HEADING)	Course in Degrees: B Gyo (COG)	Barometer in millibars	Wind: Direction	Wind: Speed	Sea State	Visibility	Lat & Long
0100	1091			142	174		340	12.7	1.5	10	11°20.62N 071°02.52
0200				146	159		341	15.9	1.5	10	11°17.3038N 71°02.3797E
0300				143	125		330	13.3	1.5	10	11°14.3757N 71°04.7404E
0400	1103			140	138		345	14.8	1.5	10	11°11.72 N 071°07.7 E
0500 20	1109			149	128		340	16	2.5	10	11°07.70N 071°12.85E
0600	1113			138	131		355	14.5	2.5	10	11°05.55N 071°15.16E

Zone Time

Notice for sea:

TIME	FUEL	WATER
0600		
1800		

Draught

Time :
Fwd :
Aft :
Max :

Figure 3: Sample of ship's log

The definitions, conventions and datums used for these measurements are unclear e.g. are distances through the water or over the ground? The following assumptions and clarifications were made:

2.2. Vessel speed/log reading

The log reading was assumed to be in units of nautical miles. The project documentation manager Dr Eric Staples, who sailed on the voyages, advised that the log readings were from GPS i.e. distance over the ground.

2.3. Heading

It was assumed that this was the angle of the ship's head relative to true north. For the purposes of this analysis it does not matter whether the datum is true, magnetic or compass north, provided the same assumption is made for all direction data.

2.4. Course over Ground (COG).

This is self-evident, with the same proviso about which reference north datum is used.

2.5. Wind direction and speed

Wind direction was relative to north, with the same proviso about which reference north datum is used. Wind speed was assumed to be measured in knots. It is not clear whether the log entries refer to true wind or apparent wind. Given that apparent wind is the quantity measured directly from the wind sensor and true wind direction requires input from other sensors, it was initially assumed that the readings were for apparent wind. However, the documentation manager had notes referring to true wind. This ambiguity could not be resolved satisfactorily, but it is not very significant in terms of interpreting the results because the vessel speed is low relative to the wind speed and the wind direction was usually on the quarter, where the difference between true and apparent direction is low.

2.6. Sea state

The values recorded were assumed to be significant wave height in metres, this being close to that which an experienced sailor would estimate visually (Lloyd, 1989).

In order to compare the ship's log readings with model test predictions, the log entries had to be filtered to avoid poor quality data. This was conducted manually by identifying those entries that showed consistent values over periods of a few hours, then listing them in a spreadsheet. The entries were then sorted by wind angle (secondarily by wind speed), see Figure 4.

date	time	SOG	hdg	COG	drift angle	drift angle	app wind dir	AWS	AWA	AWA	TWA	TWS	wave ht
		kn			=+ is to stbd	abs		kn	+ from stbd	abs		kn	m
22/5/2010	4:00:00 AM	3.1	98	117	19	19	217	10	119	119	132	12	2
24/5/2010	4:00:00 AM	3.0	84	90	6	6	207	12.6	123	123	133	14	1
9/3/2010	2:00:00 AM	4.0	103	113	10	10	341	14.2	238	122	134	17	2
12/4/2010	5:00:00 AM	3.5	185	190	5	5	301	8.2	116	116	134	10	0.5
11/4/2010	8:00:00 AM	3.8	215	222	7	7	337	12	122	122	135	14	0.5
	7:10:00 PM	3.4	147	150	3	3	25	10.2	-122	122	135	12	0.5

Figure 4: Log data sorted by wind angle

3. Comparison of ship's log with model tests.

Towing tank tests had been conducted on a 1:9 scale model by the University of Southampton Wolfson Unit (Wolfson Unit, 2008). Amongst the reported data were a resistance curve for the full-size vessel, and the output of a Velocity Prediction Program (VPP) using sail force coefficients derived from wind tunnel tests of other sailing vessels. The tank tests were conducted for three different rudder configurations: an aft rudder on the centerline, a rudder on the aft quarter, and a modified rudder on the aft quarter. The full-size vessel was fitted with both an aft rudder and a modified rudder on both port and starboard quarters.

Detailed VPP results are presented in the Wolfson report only for the centreline rudder configuration. However, the report includes a table of predicted time differences per mile between the two rudder configurations, from which a set of VPP results was derived for the quarter rudder configuration. This is not an accurate representation of the full size vessel as it does not include the additional resistance of the centreline rudder. This matter is discussed in section 4.4.

A comparison was made between the predicted and recorded vessel speeds for various wind speeds and wind angles. The log readings were sorted by TWA, then entries that lay within a range of about 5° TWA and 5kn TWS (e.g. the beige cells in Figure 4) were then grouped; then the vessel speed, drift angle and wind angle in each group was averaged.

These average values were plotted against the equivalent values from the VPP predictions. The results are shown in Figure 5.

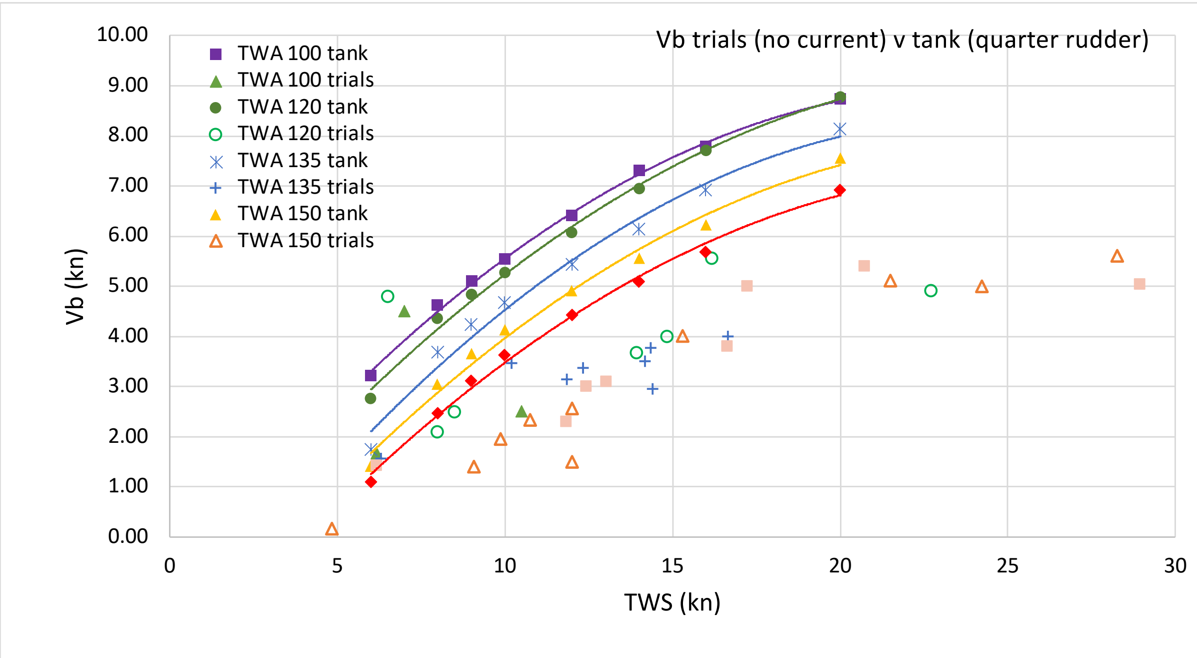


Figure 5: Comparison of vessel speeds from trials and VPP ("tank")

The graph is very busy, but it can be seen that, at any chosen wind speed, none of the vessel speeds recorded in the log are as high as the predictions (except for one outlier). A clearer view is obtained by plotting just one wind angle, as shown in Figure 6. It reveals that the vessel speeds recorded in the log are barely half those given in the predictions.

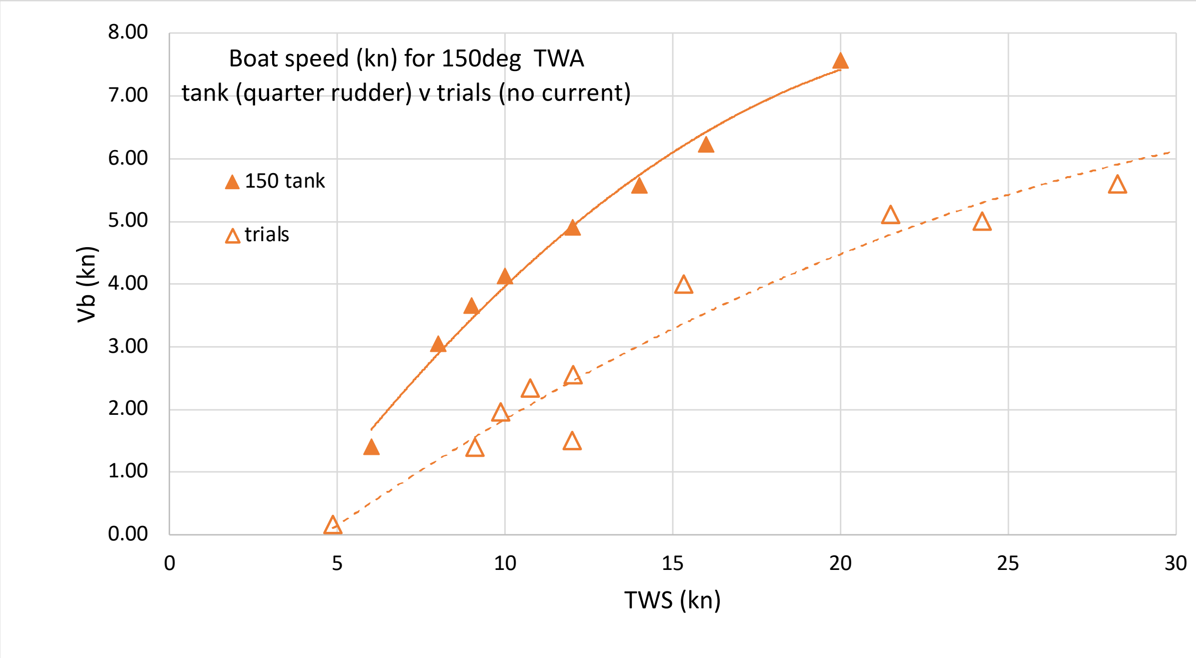


Figure 6: Vessel speed comparison log v. VPP at 150 deg TWA

The leeway angles in the ship's log, defined here as the difference between heading and course over ground, were plotted against the leeway angles predicted by the VPP, as a function of true wind angle (TWA). True wind angle was chosen as the variable because the VPP showed it to be much more influential on leeway than was vessel speed or true wind speed (TWS). The results are shown in Figure 7.

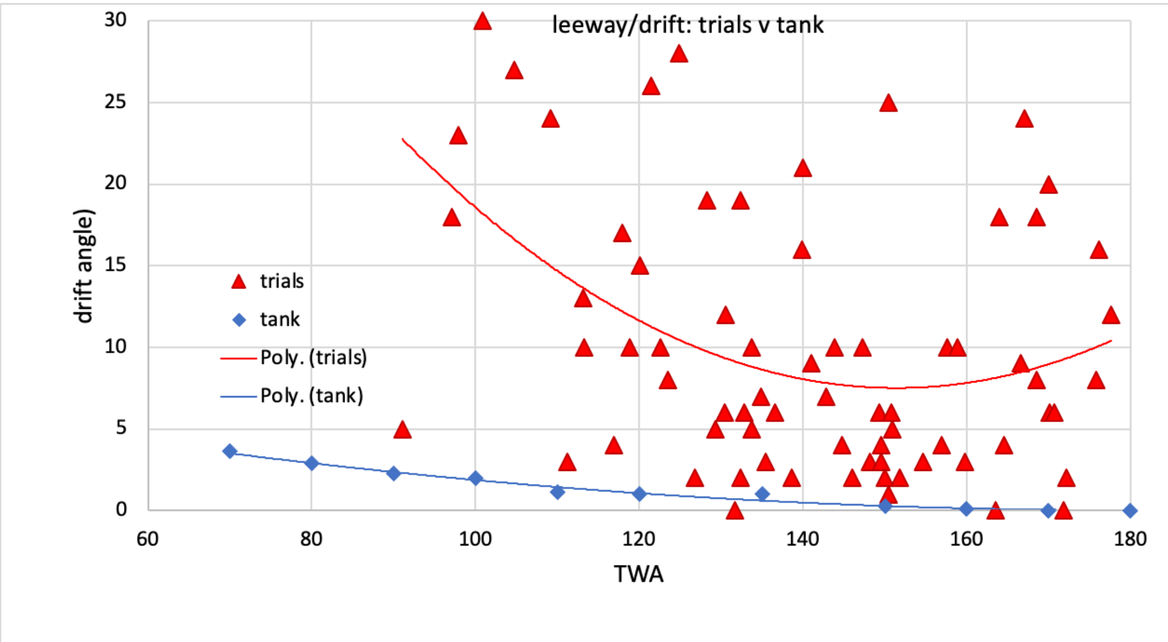


Figure 7: Leeway angle comparison log v. VPP

It is evident that the leeway angles determined from the ship's log are consistently between 5 and 10 times higher than the VPP values. It should be borne in mind that there are large uncertainties in the log leeway estimates.

The possible causes of these large vessel speed and leeway angle discrepancies are explored below.

4. Reasons for the discrepancies

Before investigating the possible causes of these large discrepancies between predicted and measured performance, it is important to acknowledge the large scatter in the ship's log data. A full error analysis has not been conducted, but 90% confidence limits are likely to be at least +-10%, probably more.

4.1. Ocean current

The distance run recorded in the ship's log is over the ground, not through the water, so it includes any ocean current effects.

Morgan & Davies (1995) shows a weak clockwise current in the north Indian Ocean for the voyage period, with a maximum value of 0.6kn. Their estimate is based on data averaged over many years. The direction is such that the current would be assisting as much as it is opposing, resulting in a degree of averaging out of current effect on vessel speed over this leg of the voyage. Yet the recorded vessel speeds are always much less than the predicted speed.

There is evidence that currents during the voyage were mostly negligible, shown by the periods in the log when the weather was calm for several hours and the vessel was almost stationary in the water, and its geographical position was also almost stationary. On the rare occasions where there was specific reference to current in the ship's log, those entries were excluded from analysis.

The measured leeway angles are very approximate, and they would be very sensitive to any cross-current that might be present. The maximum current speed predicted from Morgan & Davies (1995) is 0.6kn. The worst-case scenario for leeway error is if this maximum current were directly across the path of the vessel. The average vessel speed over the voyage from Muscat to Cochin was 2.5kn; so if the vessel were travelling at this speed with a 0.6kn cross-current, this would result in a current-induced drift angle of 14°. This worst-case scenario could account for the discrepancies in about half the data points of Figure 7. Given that it is a worst-case scenario, it is tentatively concluded that current effects could account for at most a quarter of the leeway discrepancy.

4.2. Ocean waves

Ocean waves slow a boat down when travelling to windward but slightly increase average speed when surging downwind. It is not known if wave effects were included in the Wolfson predictions. If they are, then wave effects are not a significant cause of the discrepancies. If wave effects are not included in the predictions, the recorded vessel speeds should be greater than the predictions when sailing downwind. They are not.

4.3. Hull fouling

The VPP predictions are for the hull surface with a friction allowance for the roughness of the sewn seams and the hull coating, whereas the hull will gradually foul up more as time in the water progresses, thus slowing the boat down. The effect of seam roughness was calculated by the Wolfson Unit from data in Hoerner (1965) which showed that the frictional resistance of longitudinal protuberances was equivalent to twice that on a flat surface. They calculated the combined effect of the seam protuberances and the hull antifouling/sealing compound roughness, which increased the friction resistance by 34% in total.

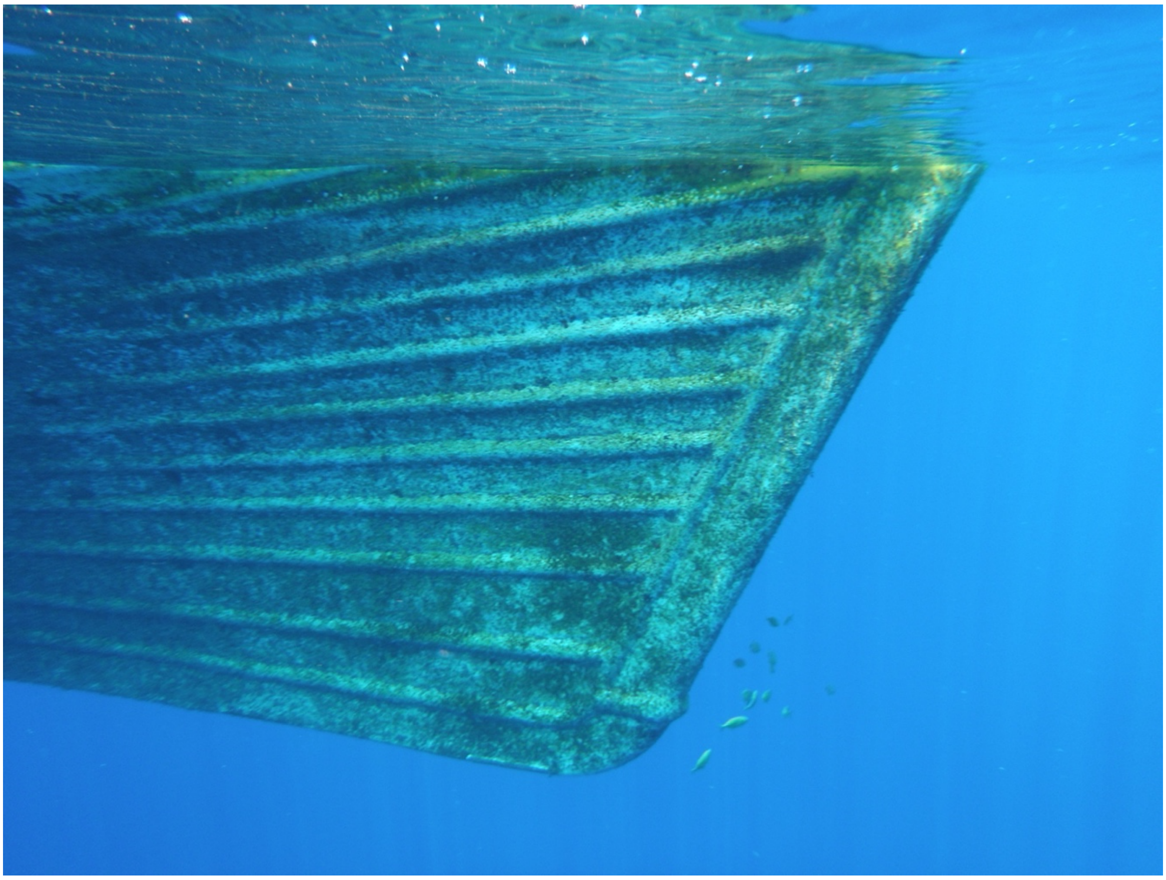


Figure 8 Seam roughness and hull fouling. Photo taken 10th March 2010. *E. Staples*

Figure 9 Haulout a Cochin late March/ early April 2010 *A Ghido*

The vessel was launched on 5th December 2009 with the hull coated in a mixture of rendered goat fat and hydrated lime. This mixture is ineffective at preventing the growth attaching to the hull compared with modern formulations, but it makes it easier to clean off (Vosmer et al, 2011). The voyage from Muscat to Cochin was from 16th February 2010 to 15th March 2010, a period of 27 days at sea. Therefore the mid-point of this voyage occurred 86 days after launching. The vessel was hauled out and cleaned at Cochin. The voyage from Cochin to Penang was from 10th April to 2nd May, a period of 22 days including a stopover at Galle.

The state of fouling on arrival at Cochin can be seen in Figure 9 and there remained significant fouling even after cleaning. In the absence of further information it is assumed that the average amount of fouling for the voyage from Cochin to Penang was the same as for the voyage from Muscat to Cochin.

Estimates of the daily rate of increase in total resistance for an un-antifouled vessel were taken from Comstock (1967) and Hoerner (1965). Both references contain estimates based on the famous *Lucy Ashton* trials of 1951, the latter reference also providing the results of a fouled flat plate towed in a tank. The estimates ranged from 0.8% to 2.3% resistance increase per day afloat.

Using the average of those fouling estimates, there was a 62% increase in resistance at the mid-point of each voyage, as compared with the Wolfson prediction of resistance. The results are plotted in Figure 10.

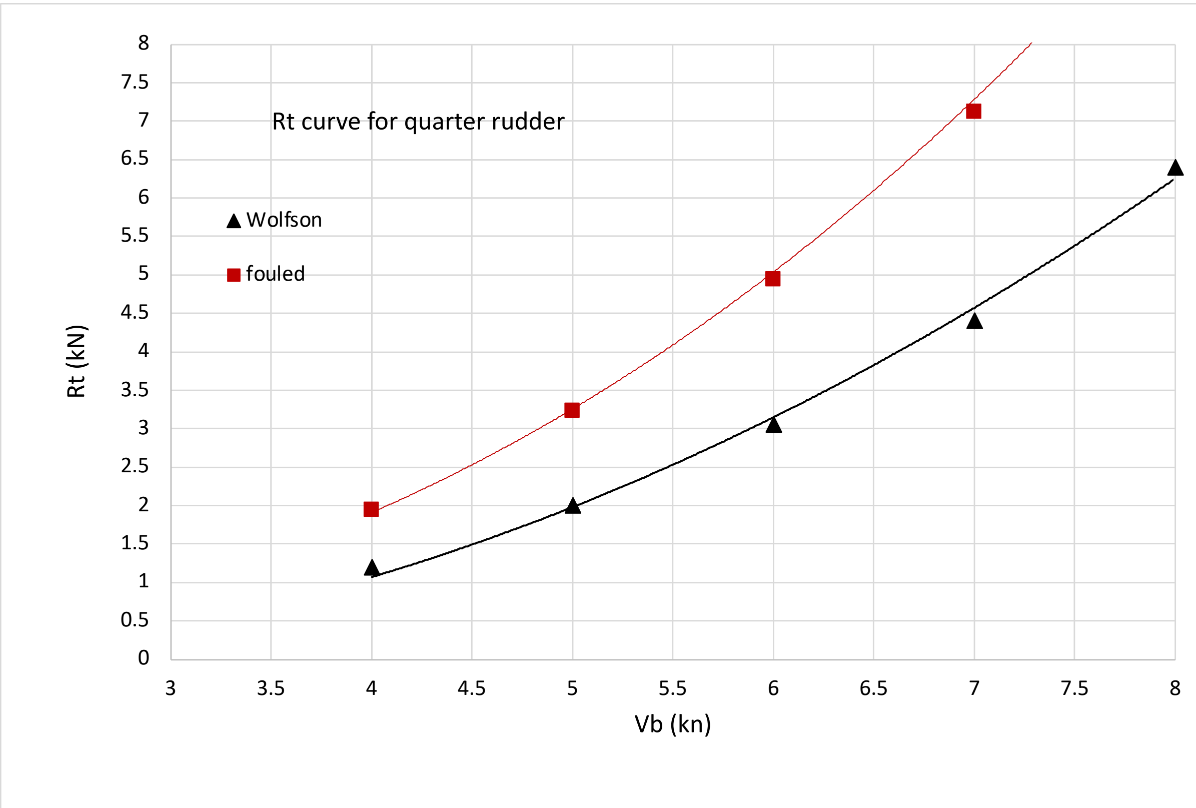


Figure 10: Resistance curve for fully fouled and lightly fouled vessel.

The measurements used for the fouling rate estimates were for fouling in water temperature of less than 16° C, whereas the *Jewel of Muscat* voyage was in much warmer waters of 20°-30° C. It is reasonable to expect that the fouling during the voyage would be greater than the rate estimated from the references above.

The effect of fouling on vessel speed can be determined by comparing intersects of each curve in Figure 10 for a chosen total resistance value (the sail thrust force is equal to the ship resistance regardless of the amount of fouling). For example, for a sail thrust of 2.5 kN the speed of the fouled vessel is 4.5kn, whereas for the unfouled vessel of the predictions it is 5.5kn i.e. a difference of 1kn. Figure 6 shows that, when the predicted speed of the vessel is 5.5kn the speed from the ship's log was 3kn i.e. a difference of 2.5kn. So on average about 40% of the speed discrepancy could be due to hull fouling.

The effect of hull fouling on leeway angle is discussed in section 4.7.

4.4. Rudder system

All the tank tests were conducted with a single rudder, either the centreline one or a quarter rudder. The vessel was equipped with a centreline rudder and two quarter rudders. Early on in the voyage it was found that the central rudder did not steer the boat effectively, so it was lashed on the centreline for most of the time. Only one quarter rudder was used at a time. The presence of the lashed centreline rudder is estimated to increase resistance by less than 1%, which corresponds to a decrease in vessel speed of less than 0.5%.

The effect of the lashed centerline rudder would be to decrease leeway angle slightly compared with the VPP predictions.

4.5. Rig efficiency

The Wolfson VPP predictions used rig forces from wind tunnel tests for "two-masted square rigs with similar aspect ratio". It is likely that those rigs are for 19th or 20th century vessels, which are quite probably more efficient than the unusual rig of *Jewel of Muscat*, thereby yielding over-prediction of vessel speed and under-prediction of leeway angle. Furthermore, the wind tunnel tests would most likely have been conducted by trimming the model sails for maximum efficiency before recording measurements, whereas the crew on the full size vessel were learning about sail setting as the voyage progressed.

4.6. Reduced sail area

It is not known if the Wolfson predictions included any assumptions about reducing sail area in the higher wind speeds, or whether those assumptions matched the sail reductions used during the voyage. The Wolfson predictions are for wind speeds up to 20kn; it is a reasonable assumption that full sail would be used for those predictions.

The crew of *Jewel of Muscat* were understandably cautious about the amount of sail they carried. They used a small storm sail a few times when the wind was very strong, and they also experimented with a smaller mizzen sail in the latter parts of the voyage. However, in wind speeds below 20kn the sails for most of the voyage were as per the original configuration.

4.7. Effect of leeway on vessel speed

The leeway angles are underpredicted by between 5° and 25° degrees. The influence of leeway on the vessel speed is an iterative effect - the slower a vessel travels (e.g. due to hull fouling), the more leeway it will make, and the more leeway it makes, the more drag will be created, slowing the boat down further, increasing the leeway etc. This could explain a lot of the vessel speed difference when the wind is at or forward of the beam. However, inspection of Figure 6 for the specific case of

150° wind angle (i.e. wind from the aft quarter) when there should be almost no leeway, shows that the recorded vessel speeds are still very much lower than the predictions. So the high measured leeway angles do not appear to have contributed to the vessel speed discrepancies.

5. Conclusions

The vessel speeds recorded on the voyage were about half of those predicted using the VPP. About 40% of the vessel speed discrepancy can be attributed to hull fouling. The effect of ocean current on the vessel speed discrepancies is much less than the effect of hull fouling. The remaining vessel speed discrepancy deficit might be due to the very steep learning curve of the crew for trimming the sails of this novel rig.

The leeway angles recorded on the voyage were often an order of magnitude greater than those predicted by the VPP. The possible presence of ocean currents would account for at most half the leeway angle discrepancy. Differences in rig efficiency could also be a contributing factor.

These considerations, when combined, highlight some of the pitfalls in comparing model scale predictions with full scale measurements.

6. Acknowledgements

I am indebted to a triad of eminent maritime archaeologists - Doctors Tom Vosmer, Eric Staples and Alessandro Ghido - for providing detailed information about the voyage including the ship's logs, the instrumentation data and their personal observations from building and sailing the vessel.

7. References

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