The effect of hull surface roughness on the performance of a model sailing yacht

Update.

This paper expands on that published in the Australian Naval Architect in May 2022. Two additions have been made:

- The effects of hull roughness in non-turbulent waters is now quantified; the previous paper assumed there was sufficient natural turbulence in the water to prevent the presence of laminar flow.
- Performance variations have been added for a typical 10 minute race. The previous paper only provided results for a 5 minute race, which is the duration of a typical of club race; National and International events tend to have longer races.

Kim Klaka 14th July 2023

Summary

The formulae used to calculate the influence of hull surface roughness on frictional resistance for ships and yachts are not applicable to model sailing yachts because the Reynolds numbers at which they operate are different. Several published formulations for the effects of hull roughness on friction were examined. The theoretical predictions of roughness effect from White (2006) are probably the most appropriate for a model racing yacht.

Results derived using formulations in White (2006) were used to predict the performance gained by smoothing the hull of a 1 m long model yacht with different grades of sandpaper. A trial was conducted to validate the results.

In open water or in small lakes with mixing sources (pumps, outboard motors etc.), the amount of environmental turbulence suggests that the incoming flow is already mostly turbulent. If the flow over the hull is fully turbulent, sanding the hull using 600 grade paper instead of 80 grade paper improves performance over a typical 5-minute model yacht race by less than one boat length.

However, if sailing in conditions of negligible environmental turbulence, such as might be encountered in still ponds, maintaining a smooth hull surface in order to promote laminar flow improves performance over a typical 5-minute model yacht race by 2-3 boat lengths.

The effects of surface roughness on the generation of sideforce were not examined.

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1. NOMENCLATURE

AR_E	effective aspect ratio
AR_G	geometric aspect ratio
C_F	friction coefficient
ΔC_F	increase in friction coefficient due to surface roughness
C_L	lift coefficient
d	grain size diameter (μm)
f	friction factor
h_s	sublayer thickness
H	boundary layer shape factor = displacement thickness/momentum thickness
k	roughness height (m and μm)
L	waterline length (m)
Re	Reynolds number
Tu	turbulence factor
x	distance from leading edge (m)
X_{tr}	transition point distance from leading edge (m)
V	flow velocity, boat speed (m/s)
υ	kinematic viscosity (m^2/s)

2. THE QUESTIONS TO BE ANSWERED

Those readers who are not familiar with the fluid mechanics of flow over a solid surface should read Appendix A before proceeding further.

Is laminar flow present?

The hull of a typical 1m long model sailing yacht operates at Reynolds numbers from about 4×10^5 to 2×10^6 which is close to, or within, the laminar flow range. There are at least two subsequent questions that need to be answered before any conclusions can be drawn:

- Is the flow already turbulent when it reaches the hull?
- Is the hull too rough to maintain laminar flow for any significant length?

It might be thought that these questions have already been answered through towing tank tests on scale model ships. There are two reasons why this is not the case:

- Most tank models are larger than model sailing yachts and the tests are conducted at Reynolds numbers three or four times higher than those of model sailing yachts.
- The towing tank model problem is the inverse of the sailing model yacht problem. In the towing tank it is necessary to trip the flow from laminar to turbulent near the bow, thereby maximising the extent of turbulent flow and thus simulating the flow conditions on the full-size vessel. The aim for the model sailing yacht, on the other hand, is to minimise the extent of turbulent flow.

If laminar flow exists over most or all the model sailing yacht hull, conventional hydrodynamic theory (backed by experiments) states that roughness does not increase drag in laminar flow, so roughness will not increase drag on the model yacht. If this is true, then it is unnecessary to sand down the hull. However, if the Reynolds number is near the critical value for transition, there is the potential for improved performance through delaying transition by sanding the hull smooth.

How much does roughness in a turbulent boundary layer affect speed?

As with the first question, it might be expected that this one is readily answered by applying pre-existing formulations used for ships and yachts. As shall become evident, this does not work.

In the following analysis, the hull is assumed to have no pressure gradient. Whilst this is not strictly correct, it does make the analysis manageable and is a reasonable approximation for a slender hull sailing in line with the flow i.e. no leeway.

The flow over the keel or rudder of a model yacht requires different assumptions to be made. It is not addressed in the main body of this article, but an introduction is given in Appendix B.

3. ROUGHNESS HEIGHT DISCREPANCIES AND SANDPAPER GRADE

Before the hydrodynamics of the problem is explored, there is an issue regarding the estimation of hull surface roughness height. The roughness height for different surface finishes is quoted in a variety of texts, but they do not always state what measure of height is being used e.g. rms height, maximum height or some other measure of height. The values shown in Table 1 illustrate the problem.

Type of surface finish	van Oossanen (2018)	Larsson et al (2014)	Massey (1979)	Hoerner (1965)	Schultz (2002) max	Schultz (2002) rms
sanded with 600 grit then polished	0.2			0.5	2	0.27-0.3
sanded with 600 girt	0.73				8-9	0.67-0.73
sanded with 400 grit	0.77				8-9	0.70-0.77
sanded with 60 grit	1.63				12-13	1.43-1.63
AC racing yacht	1					
standard racing yacht, 400 grit cleaned daily	2					
painted but not sanded	5	50-100		5-200	39-50	3.4-5.0
primed new steel plate	40-60		45	50		
flat plate sprayed with antifoul paint	40-75					
cast iron	250		250	250		

Table 1 Roughness height (μm) for different surfaces

The figures from van Oossanen are stated to be "average" values. The values for Schultz are given as ranges because they vary with the length over which the sample is measured. It should be borne in mind that the height and length scale of the roughness are not the only roughness parameters correlating with increased friction. The shape of each protrusion and the density distribution of the roughness also influence friction. This is the subject of considerable ongoing research (e.g. Harvald, 1983; Howell & Behrends, 2006) and lies beyond the scope of this paper.

The large disparities shown in Table 1 and the lack of clarity in the definitions of the roughness heights quoted make it difficult to apply these data reliably to friction formulations.

There is another anomaly, which is more easily clarified. When sanding with a particular grit size of sandpaper, the roughness height generated is an order of magnitude less than the diameter of the grit in the paper (see Table 2).

	surface roughness height k (μm)		**grain size (μm)**	
ISO sandpaper grade	**k rms (Schultz)**	**k max (Schultz)**	**average particle diameter (Wikipedia)**	**particle diameter (Grainger)**
P600	0.67-0.73	8-9	26	26
P400	0.70-0.77	8-9	35	36
P220	0.74-0.86	9	68	
1P20	0.9-1.02	9-10	125	
P80			200	190
P60	1.43-1.63	12-13	270	265
unsanded painted	3.4-5.0	39-50		

Table 2: Sandpaper roughness and surface roughness

From the above data, the relationship between paper grade and grain size can be approximated as:

$$paper\ grade = \frac{15500}{d} \qquad \text{Equation 1}$$

where d = grain size diameter (μm)

and the relationship between paper grade and maximum roughness can be approximated as:

$$k_{max} = \frac{22}{paper\ grade^{0.15}} \quad \text{Equation 2}$$

4. ENVIRONMENTAL TURBULENCE

The question arises as to whether the water in which a model yacht sails already contains turbulence caused by wind, waves, current, and anthropogenic factors (ship wakes, propeller vortices etc.). Such turbulence will inhibit the presence of laminar flow, and may completely eliminate it. How likely is this?

Environmental turbulence can be characterised by the parameter Tu, which is the ratio of velocity perturbations to the mean velocity. For a yacht moving through water, the mean velocity in the denominator is dominated by the boat speed of the yacht. If this is the case, the slower the boat speed the higher the value of Tu in a given body of water. It follows that the turbulence factor Tu for a model yacht will be as much as one order of magnitude higher than it is for a (much faster) full size yacht travelling in the same body of water.

Hoerner (ch10-2 fig 2) shows experimental results for the same foil tested in a wind tunnel and a towing tank. The friction coefficient measured in the tunnel is a lower value than that measured in the tank at the same Reynolds number, until the Reynolds number is high and both are in turbulent flow. This implies that water in a towing tank has natural turbulence that inhibits or prevents laminar flow being established.

Vijgen et al (1992) report that in the upper layers of the ocean the natural Tu is between 0.1% and 1.2%. (This paper also provides an interesting insight on the effects of environmental turbulence on laminar flow foil sections for yachts.) If the Tu for a model yacht in this environment is one order of magnitude higher, it will experience a Tu of between 1% and 12%. Van Oossanen (2018) states the critical Reynolds number for transition is halved when Tu increases from 0.1% to 0.35%. White (1974) states that for a Tu of 0.6% the transition Reynolds number is 1×10^6, which is a value typical of model yacht sailing conditions. Also, when Tu increases from 0.08% to 3%, the transition Reynolds number decreases from 2.8×10^6 to 1×10^5.

These findings suggest that there is likely to be sufficient turbulence, in open expanses of water at least, to eliminate the presence of laminar flow. Yacht designer David Pedrick, who has dealt with this question of environmental turbulence during several America’s Cup efforts, feels that the environmental turbulence largely negates the development of laminar flow. “We’ve used electronic sensors and microphones to test for laminar flow,” he says. “You can get some, but not much.” https://www.gp14.org/a-smooth-bottom-is-a-fast-bottom/

I have not yet found information on the amount of environmental turbulence in ponds of the size used by a model yachts. This could be for the reason given in MacIntyre et al (2018): "Studies of the mixing dynamics of ponds are rare". The value of natural Tu would have to be less than 0.6% for there to be any chance of laminar flow, which is midway in the range of values for open waters. The short fetch and correspondingly small, non-breaking, waves on model yacht ponds will result in much less mixing than in open waters if there are no external mixing sources (e.g. pumps, outboard motors), implying a correspondingly lower value of Tu. This increases the possibility of laminar flow existing, compared with the environment in which "big boats" sail.

5. EFFECT OF ROUGHNESS WITHIN LAMINAR FLOW

Most fluid mechanics text books show that roughness does not affect friction in laminar flow, therefore roughness does not matter until transition is reached. This widely accepted conclusion is supported by several theories backed up by experimental results. A universally recognised equation for calculating friction drag in laminar flow is the Blasius formula (Massey 1979, van Oossanen 2018, White 2006):

$$C_f = \frac{1.328}{\sqrt{Re}} \qquad \textit{Equation 3}$$

The assumption that laminar flow friction is independent of surface roughness is becoming increasingly open to challenge. Gloss &Herwig (2010) looked at micro flows (but it is applicable to macro flows), showing that roughness increases friction in laminar flow as well as in turbulent flow, but through very different mechanisms. They measured and modelled the friction drag for varying roughness heights in both laminar and turbulent flow between two flat plates. The numerical values for Reynolds number and roughness are not easily adapted to the case of a single flat plate, but they show that roughness does increase friction drag in laminar flow.

6. EFFECT OF ROUGHNESS ON TRANSITION POINT[1].

If laminar flow is possible over at least some of the hull, then it would be very useful to know just how much laminar flow there is. Hoerner (ch2-9 fig 10) suggests that the critical roughness height k_{crit} which causes transition from laminar to turbulent flow is given by:

$$\frac{10^4 k_{crit}}{x_{tr}} = about\ 2.5 \qquad \textit{Equation 4}$$

The constant 2.5 varies from 2 to 4.

The disadvantage of this equation is that the location of the transition point must be known in order to find out what the critical roughness height is that causes the transition.

Estimates from model experiments for the transition point on a smooth surface vary quite a lot, probably because of slight pressure gradients, slight roughness, and the level of environmental turbulence.

Hoerner suggests the transition Reynolds number lies somewhere within 0.5->0.6 x 10^6. He also states that for constant pressure surfaces the transition Reynolds number is “in the order of 2.4 x 10^6 ” and that laminar flow is always stable at Reynolds number below 6 x 10^4. White (2006) reports that the transition Reynolds number is 2.8 x 10^6 for a smooth plate when the environmental turbulence is a low 0.02%. He also provides data showing that the transition Reynolds number decreases by one order of magnitude for the range of roughness heights of interest here.

Van Oossanen (2018) and White (2006) provide a method for estimating the transition point as a function of the boundary layer shape factor H (equation 4), though White states "This method is not well verified versus experiment".

$$log_{10}(Re_{tr}) \cong -40.4557 + 64.8066H - 26.7538H^2 + 3.33819H^3 \qquad \textit{Equation 5}$$

7. EFFECT OF ROUGHNESS WITHIN TURBULENT FLOW

Critical roughness height

If the flow is turbulent, there is considered to be a critical roughness height below which the roughness has no impact on friction. The critical roughness height can be determined by using the traditional assumption that the surface is hydraulically smooth if the roughness height does not protrude through the laminar sub-layer that exists within the turbulent boundary layer. The notion that a surface is either hydraulically smooth or "fully rough" is a good approximation for high Reynolds number flows, but it may be too simplistic for the lower Reynolds numbers of a model yacht. "Fully rough" is a concept which might be described as when the roughness height is sufficient to fully disrupt or destroy the laminar sub-layer. There is clearly an intermediate roughness height which increase friction slightly but does not completely destroy the laminar sub-layer. This intermediate roughness height is of little interest to full size vessels but it lies at the core of the model yacht hull smoothness question.

The formula for the sub-layer thickness from Larsson et al, (2014) is:

$$h_s = \frac{10^{-4}}{V} \qquad \textit{Equation 6}$$

where

h_s = sub-layer thickness (m)

V = boat speed (m/s)

The sublayer thickness was estimated by Schlichting (in Olson, 1973 and Harvald, 1983) to be:

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[1] It is worth noting that transition does not occur at a single point, rather it has two boundaries. The first is where transition to turbulent flow starts to develop in isolated locations and the second is where the flow everywhere downstream is fully turbulent.

$$h_s = \frac{100\upsilon}{V} \qquad \text{Equation 7}$$

where:
h_s = sublayer thickness (m)

υ= kinematic viscosity (m^2/s)

V = flow speed (m/s)

Neither of the above equations include any length term, whereas qualitative descriptions of the sublayer describe how the thickness increases along the surface. Hoerner (1965) provides a formula which includes a weak dependence on length:

$$\frac{h_s}{x} = \frac{105}{Re_x^{\frac{11}{12}}} \qquad \text{Equation 8}$$

where:
x = distance from the leading edge of the plate (m)

Re_x = Reynolds number based on x.

The sublayer thickness can also be inferred from formulations for friction increase, as it corresponds to the roughness height at which the friction increase tends to zero (see section 8 and Table 6).

Friction coefficient

Nikuradse pipe experiments

The effect of roughness on friction drag was first quantified by Nikuradse (1933) in experiments on flow through pipes. His famous graph, often called a Moody chart, forms the basis of friction curves found in many text books,. e.g. Figure 1

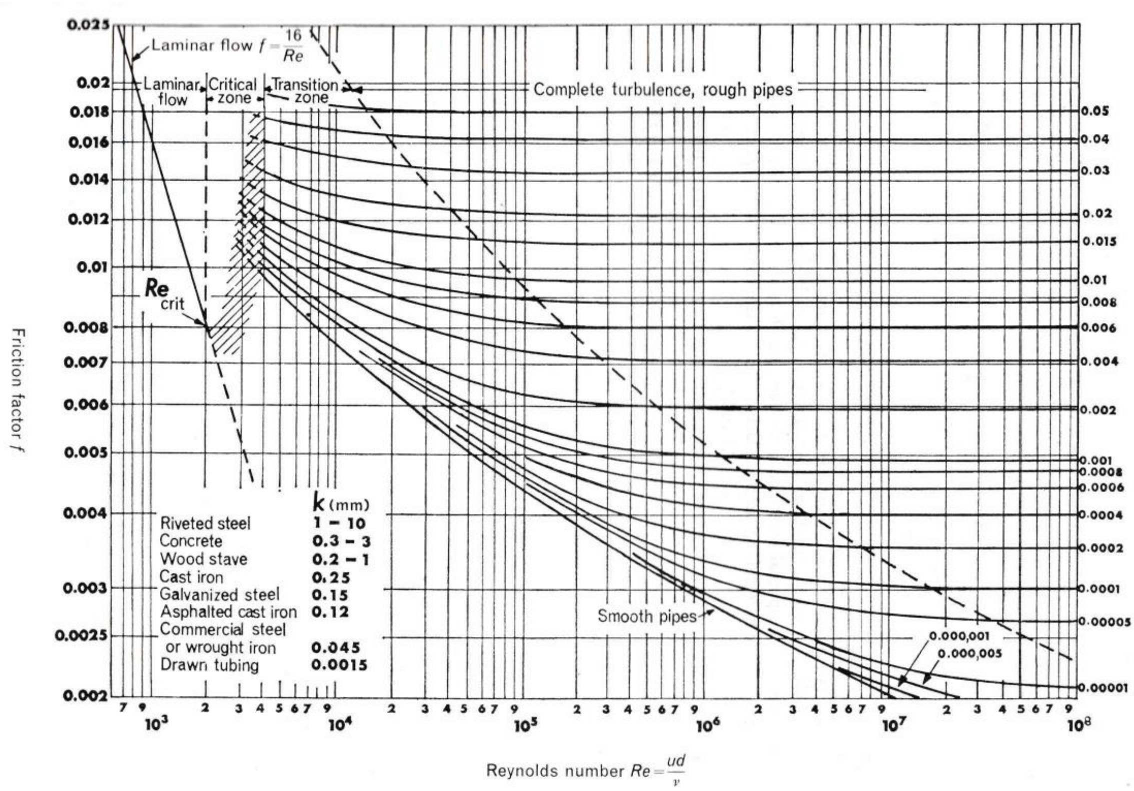

Figure 1: Typical friction curve (Massey,1979))

Note that the Darcy friction factor f on the vertical axis is 4 x C_F (White, 1974), and the Reynolds number on the horizontal axis is based on pipe diameter, which is not the equivalent of boat length - there is more than one order of magnitude difference.

The graph shows that, as roughness height increases so does the friction. It also shows that the increase in friction is independent of Reynolds number for the values at which most ships and yachts operate. When the flow is in this condition it is considered to be fully rough, and the independence from Reynolds number makes calculation of friction in these conditions quite straightforward.

Unfortunately model yachts operate at much lower Reynolds numbers, never reaching the fully rough condition unless large protuberances are added to the surface. Furthermore, the roughness curves in the Moody chart for the Reynolds number regime of relevance to model yachts are poorly delineated, and in some instances, absent. This is probably due to lack of data in this region.

1978 ITTC method

There are several formulations for evaluating the effect of increasing roughness on friction for fully rough flow, but model yachts do not operate in fully rough flow. The 1978 ITTC method (Harvald, 1983) is presented here because the results (in section 8) show how misleading they can be for model yachts.

$$\Delta C_F = \left[105\left(\frac{k}{L}\right)^{0.333} - 0.64\right] \times 10^{-3} \qquad \textit{Equation 9}$$

Harvald defines k as "the mean apparent amplitude of the surface roughness over a 50mm wavelength". On inspecting the source from which this definition arrives, (British Ship Research Association, in Harvald), it is the mean of the maximum amplitudes, not the mean amplitude.

Van Oossanen

van Oossanen (2018) has developed an approximate formula for friction coefficient as a function of Reynolds number and roughness height, which has neither a terminal value at high Reynolds number nor a minimum critical roughness height i.e. the smoother the surface, the lower the friction. This alternative formula is:

$$\Delta Cf = a[log10(Re)]^b \qquad \textit{Equation 10}$$

Where a and b are functions of a Reynolds number which uses the roughness height for its length dimension.

The range of Reynolds number for which this formula is applicable is not stated, but the presence of Reynolds number in the equation indicates that it might be applicable to flows that are less than fully rough. Results are given for Reynolds number as low as 10^6, which is representative of model yacht conditions.

If equation 9 is valid for model yachts, there is no limit as to how smooth the hull should be.

Schultz

Experimental work conducted by Schultz (2002) deserves close attention for two reasons. Firstly, the experiments were conducted very carefully and the roughness of the surface was rigorously categorised. Secondly, and of particular relevance to this paper, the surface roughness was not created by adding roughness particles; rather it was developed by sanding a painted surface with increasingly finer grades of paper. This is the same technique used by sailors to finish a hull surface. Unfortunately, the lowest Reynolds number in the Schultz experiments was ~2.8 x 10^6, which lies just beyond the operating regime of a model yacht.

White

White (2006) derives a formulation which is for all turbulent flow conditions from hydraulically smooth to fully rough.

$$Re = 1.73125(1 + 0.3k^+)e^{0.4\lambda} \times \left[Z^2 - 4Z + 6 - \frac{0.3k^+}{1+0.3k^+}(Z-1)\right] \textit{Equation 11}$$

where:
$Z = 0.4\lambda$

$$\lambda = \sqrt{\frac{2}{C_F}}$$

$$k^+ = \frac{Re\left(\frac{k}{L}\right)}{\lambda}$$

The roughness height k is defined by White as the average size of a grain attached to the surface. As with Equation 9 of van Oossanen, inspection of equation 10 shows that there is no critical roughness height. If the roughness height is set to zero, the results follow the same trend as for standard smooth-turbulent formulations (Nikuradse etc.). The White equation is considered the most likely to yield valid results for turbulent flow over model yacht hulls. (Note that this equation is from the 3rd edition of White; the one in the 2nd edition contains an error).

8. NUMERICAL RESULTS

The formulae in the previous section have been applied to a model yacht with a hull waterline length of 1 m. Four speeds were investigated:

Sailing condition	approx. boat speed (kn)	boat speed (m/s)	Reynolds number
Light airs sailing	1	0.5	4.2×10^5
Windward sailing	2	1.0	8.4×10^5
Hull speed	2.5	1.3	1.1×10^6
Planing	4	2.0	1.7×10^6

Table 3: Sailing speeds investigated

Transition point

The location of the transition point, assuming a smooth surface with no pressure gradient, was calculated from three different sources using the upper (fully smooth) and lower (fully rough) bounds for transition. The results are shown in Table 4.

L = 1m		**x_{tr} (m)**			
		light airs	**upwind**	**hull speed**	**planing**
	V (m/s)→	*0.5*	*1.0*	*1.3*	*2*
Hoerner rough		0.14	0.07	0.05	0.04
Van Oossanen rough		1.62	0.81	0.62	0.41
White rough		0.67	0.33	0.26	0.17
average rough		*0.81*	*0.40*	*0.31*	*0.20*
Hoerner smooth		5.71	2.86	2.19	1.43
Van Oossanen smooth		11.48	5.74	4.40	2.87
White smooth		6.66	3.33	2.55	1.67
average smooth		*7.95*	*3.98*	*3.05*	*1.99*

Table 4: Transition point distance from bow

The results show that:

- if there is negligible environmental turbulence and the hull is smooth, then the entire hull will be in laminar flow.

- even if the surface is rough, between 20% and 80% of the hull will be in laminar flow provided there is negligible environmental turbulence.

Therefore there is potential benefit in maintaining a smooth surface to promote laminar flow, but only if sailing in conditions of negligible environmental turbulence.

Critical roughness

Some critical roughness estimates for a hydraulically smooth surface in turbulent flow are shown in Table 5.

		light airs	**upwind**	**hull speed**	**planing**
L = 1m	*V (m/s) →*	*0.5*	*1.0*	*1.3*	*2*
Eqn 5 (Larsson)	k_{max} (μm)	200	100	77	50
Eqn 6 (Olson)		238	119	92	60
Eqn 7 (Hoerner)		735	389	306	206

Table 5: Critical roughness (sub layer thickness) in microns

All these values are considerably higher than the roughness of an unsanded painted surface (see Table 2), implying that there is no advantage in sanding down even the roughest of paint finishes.

However, Schultz (2002) found that there is a decrease in friction drag as increasingly finer grades of sandpaper were used, terminating once 400 grade paper was used. Table 2 shows that sanding with 400 grade paper creates a roughness height of 8 microns.

Drag increase above critical roughness

When using the data and equations discussed in section 4, the question arises as to whether the roughness length dimension k is the rms value, the maximum value, or some other value. This was resolved by plotting the friction increase against roughness height for the Schulz experimental results and comparing them with the output of equation 10. The results in Figure 2 show clearly that the roughness dimension used in equation 10 cannot be the rms value, and that using the maximum roughness height yields realistic results.

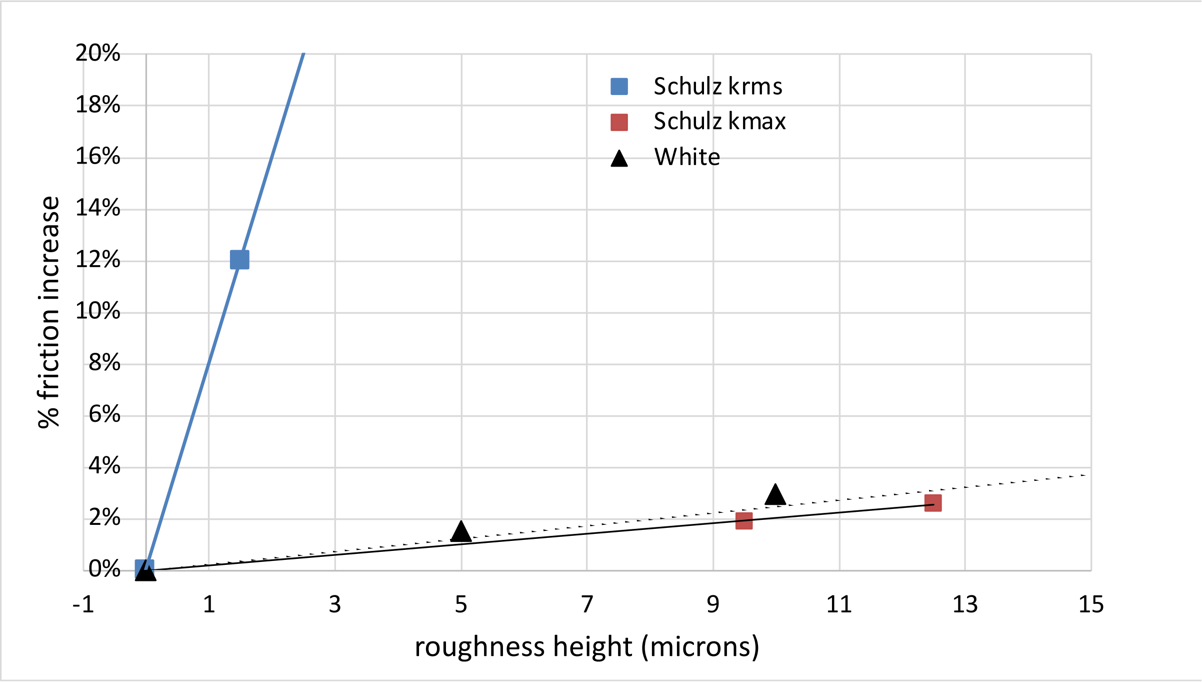

Figure 2: Effect of roughness parameter on friction results

Having made this determination, the increases in friction due to roughness from sources discussed in section 4 were estimated at a boat speed of 1.3 m/s (hull speed); the results are shown in Table 6.

Roughness height (μm)	**van Oossanen (2018)**	**Schultz (2002)** **k = k_{max}**	**White (2006)**	*ITTC* *(fully rough)*	*Gloss & Herwig (2010) (laminar flow)*
2	0.05	<1.0	0.5	15	
10	0.9	1.9	2	36	9
50	5	5	9	71	7
100	8		16	90	
200	15		27	120	

Table 6: % Change in friction drag at Re ~= 10^6

The percentage increases in friction for laminar flow from (Gloss & Herwig, 2010) are similar to some of those in turbulent flow. However, the absolute values of drag increase are low because the drag in laminar flow is much lower than in turbulent flow.

When discussing the results it is important to bear in mind the following:

- The van Oossanen results might be applicable to model yachts, though it is not clear.
- The Schultz results are for Reynolds numbers higher than those experienced by model yachts.
- White is valid for Reynolds numbers and roughness regimes typical of model yachts.
- The ITTC values are for the fully rough condition, not normally found in model yachts.
- The Gloss & Herwig results are for laminar flow only.

Taking into account those constraints, it can be seen that:

- the ITTC "big ship" formulation considerably overestimates friction increase due to roughness.

- roughness heights below about 5 microns create negligible friction increase in a turbulent boundary layer.

It is considered that the White formulation of equation 11 is appropriate for both model and large yachts. This view was partially tested by applying the equation to a full-size sailing yacht for which Larsson et al (2014) provide graphical data. The results agreed to within 8%.

Equation 11 was then applied to a model yacht scenario, yielding the results shown in Figure 3.

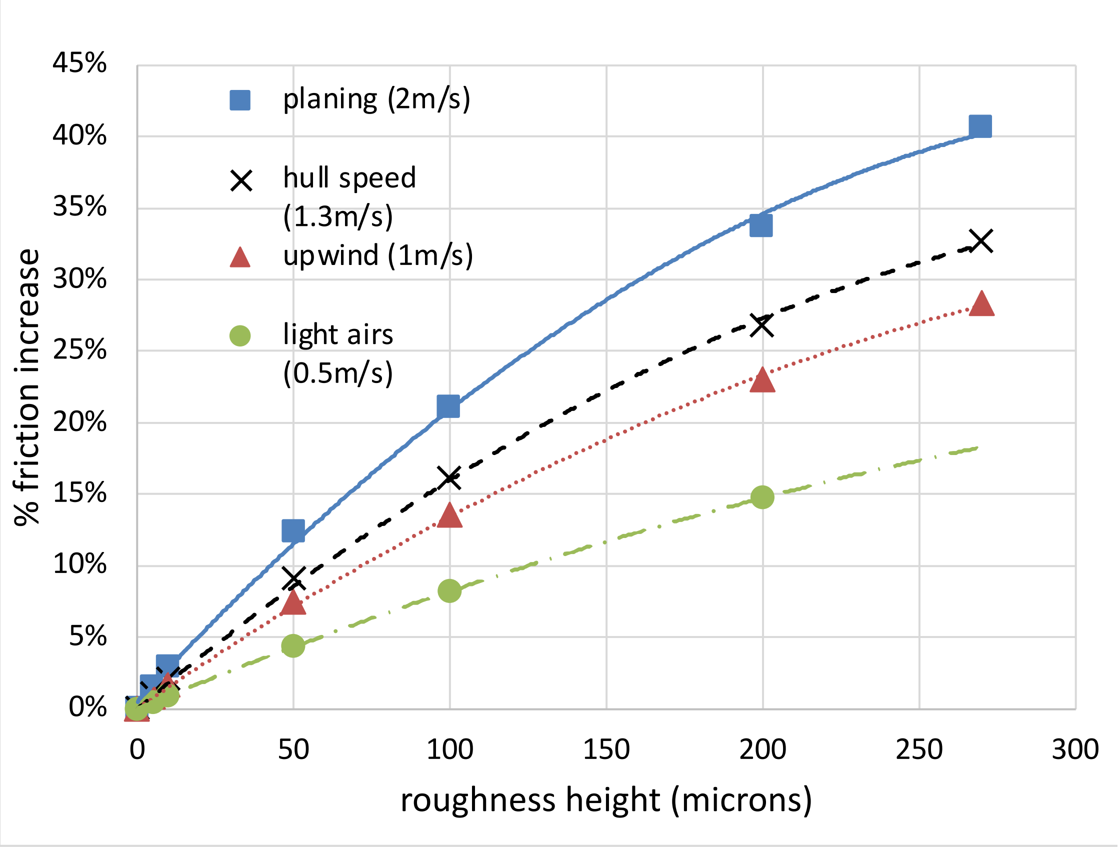

Figure 3: Effect of roughness height on friction (equation 11) in turbulent flow

9. PREDICTED EFFECT OF HULL ROUGHNESS ON BOAT SPEED

Calculating the friction increase due to roughness is not the end of the task; it is the speed loss on the race course that is of ultimate interest. The impact of a given increase in friction on boat speed depends on several factors, including:

- the proportion of total drag attributable to friction drag,
- the relationship between drag and boat speed, and
- the impact of a reduction of boat speed on other components of drag.

A Velocity Prediction Program (VPP) was used to investigate the effect of friction increase on performance. The calculations were performed by Bantock (2021) using the Win Design VPP https://clayoliveryachtdesign.com/windesign-vpp . The yacht modeled was a DF95, the same as was used in the full scale trials described in the next section. The friction increase for different roughness heights or the presence of laminar flow was simulated by changing the wetted surface area. Sample results are shown in Figure 4.

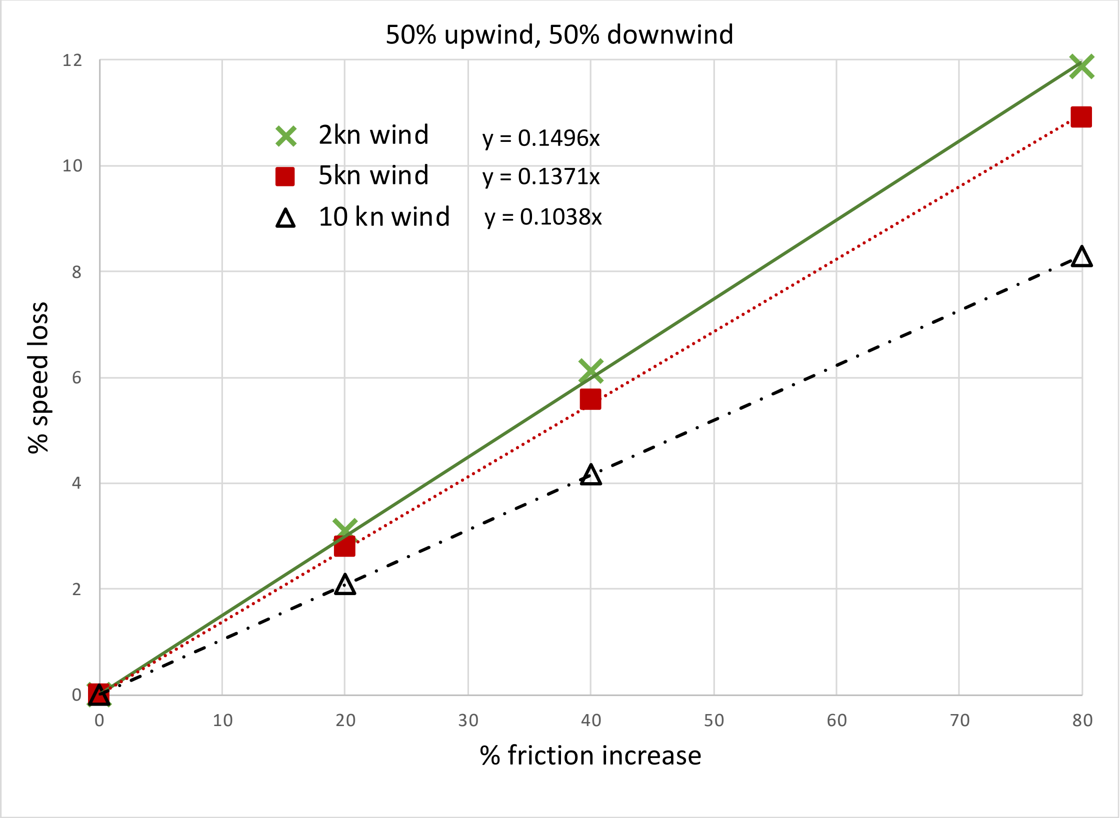

Figure 4: Effect of friction increase on speed loss

It is important to note that this assumes:

- there is no pressure gradient over the hull, and
- the influence of roughness on the foils is not considered here.

Fully turbulent flow

By obtaining best-fit linear trendlines for the data in Figure 4 and combining them with equations 2 and 10, the percentage speed change in turbulent flow can be calculated for a hull sanded down with different grades of sandpaper. The resulting speed differences have been applied to a typical model yacht racing course of 90m leg length, two laps upwind and downwind. The results for a wind speed of 10 kn are shown in Figure 5, in terms of boat lengths lost on the course compared with a fully smooth hull.

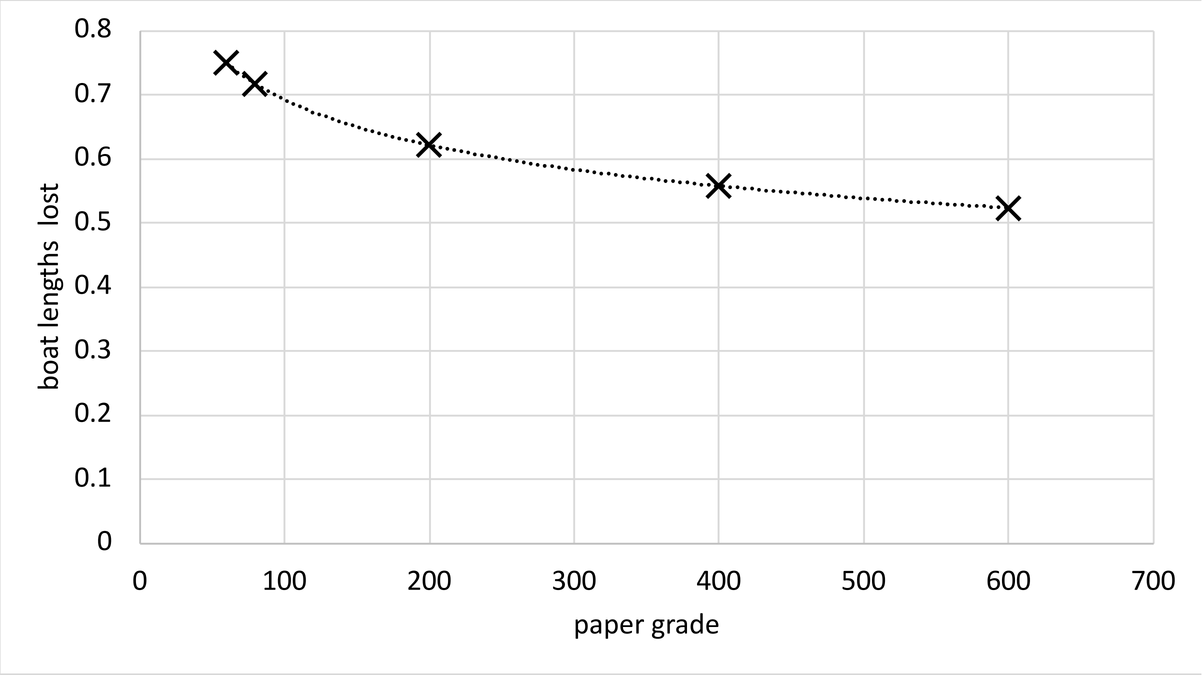

Figure 5: Effect of sandpapering on distance lost – turbulent flow

The surprising observation is that sanding the hull using 600 grade paper instead of 80 grade paper improves performance over the course by less than half a boat length. For a 10 minute race the performance improvement is still less than one boat length.

Laminar flow present

If there is negligible environmental turbulence then laminar flow may exist over part or all the hull (see Table 4). The friction drag for the sailing conditions given in Table 3 have been estimated using the following procedure:

- Use the transition point distances calculated from White (2006) in Table 4. There are just two values – rough and smooth. These are considered to approximate a well-painted but unsanded finish (about 10 μm), and a mirror-sanded finish (about 2 μm).
- Assume the ratio of wetted surface areas in laminar and turbulent flow is the same as the ratio of the lengths in laminar and turbulent flow.
- Assume that surface roughness does not affect friction within laminar flow. The friction coefficient in laminar flow is calculated using the Blasius formula (equation 3). The length dimension used in the Reynolds number is the distance to the transition point.
- The friction coefficient in the turbulent flow regime is calculated using the White formula (equation 11).
- The friction coefficients for the two regimes are weighted according to the length of each regime to yield a total friction coefficient.

The results for the two surface finishes are compared with the corresponding friction coefficients already calculated for fully turbulent flow (Figure 3), and with each other.

The above procedure is not scientifically or mathematically robust, but it is considered a useful engineering approximation. The advantage of the smooth hull (approximately2 μm, 1200 grade paper) over the rough hull (approximately 10 μm, 200 grade paper) for a typical upwind/downwind race in 10kn true wind speed, are shown below :

	5minute race	**10 minute race**
No laminar flow	0.5 boat lengths	1 boat length
Laminar flow possible	2.3 boat lengths	4.5 boat lengths

Table 7. Advantage of smooth finish over rough finish

10. FULL SCALE TRIALS VALIDATION

A qualitative trial was conducted using a Dragonflite 95 radio sailing yacht https://dfracing.world/. The yacht is 0.95 m length overall. The yacht was firstly raced in two regattas with a very smooth bottom to establish benchmark performance. The smoothness was estimated as 2 microns, achieved by sanding progressively through sandpaper grades down to 1200, then finishing with cutting compound to obtain a "matt mirror" finish. A rough surface finish was then applied, comprising spherical particles of approximately 60-80 grit size, densely packed in varnish applied by brush. The 60-80 grit particles correspond to a roughness height of about 235 microns (Table 2). The boat was raced with this surface finish in a third regatta, then the varnish mix was removed and the hull sanded back to the original matt mirror finish and raced again in a fourth regatta. The regatta results are shown in Table 8.

Regatta no.	**no. of boats**	**overall placing**	**best race**
1 (smooth hull)	6	2nd	1st
2 (smooth hull)	6	1st	1st
3 (rough hull)	9	7th	3rd
4 (smooth hull)	8	3rd	1st

Table 8: Regatta results

The races conducted with the varnish-grit finish were held on the Swan River at South of Perth Yacht Club, Western Australia on Friday 15th Oct 2021 with 9 boats competing. They were mostly the same boats raced against before and after that date, so they provided a reasonable benchmark. The course was windward-leeward (2 laps), with the distance from top to bottom mark about 90 m. Winds were light with periods of calm (2-5kn recorded at the nearby on-water weather station). There was partial wind shadowing from nearby jetties. The water surface was quite glassy except for the occasional wake from a passing power boat. The natural environment was considered turbulent. The grit surface stayed intact for the duration of the racing.

During the first, second and fourth regattas, with the smooth hull, boat speed upwind was usually amongst the best in the fleet, downwind it was about average. During the third regatta, with the varnish-grit finish applied, boat speed upwind and downwind was slower than every other boat. The boat had definitely lost its sparkle, similar to when the rig tune is completely wrong.

The average speed loss during the rough hull trial was evaluated by estimated distance lost over the course, then converting that to boat speed loss. This resulted in an estimate of 5% boat speed loss. This observed speed loss of 5% is reasonably close to the 4% loss predicted by the VPP for light winds using the data from Figure 3 and Figure 4. This provides some validation for the theoretical predictions of roughness effect from White (2006).

11. CONCLUSIONS

- The amount of environmental turbulence in open water suggests that the incoming flow is already mostly turbulent. This might not be the case for enclosed ponds.
- The predictions of roughness effect from White (2006) are probably the most appropriate for a model racing yacht.

- If the flow over the hull is fully turbulent, sanding the hull using 600 grade paper instead of 80 grade paper improves performance over a typical 5-minute model yacht race by less than one boat length.
- If sailing in conditions of negligible environmental turbulence, such as might be encountered in still ponds, maintaining a smooth hull surface in order to promote laminar flow improves performance over a typical 5-minute model yacht race by 2-3 boat lengths.

12. ACKNOWLEDGEMENTS

Thanks are extended to Graham Bantock of SAILSetc for running the VPP and offering technical advice, including how best to create the hull rough surface for the sailing trial. Thanks are also due to Dr Tim Gourlay of Perth Hydro for suggestions on how best to solve the transcendental equation 10 of White, which confirmed my belief that mathematics is mystical.

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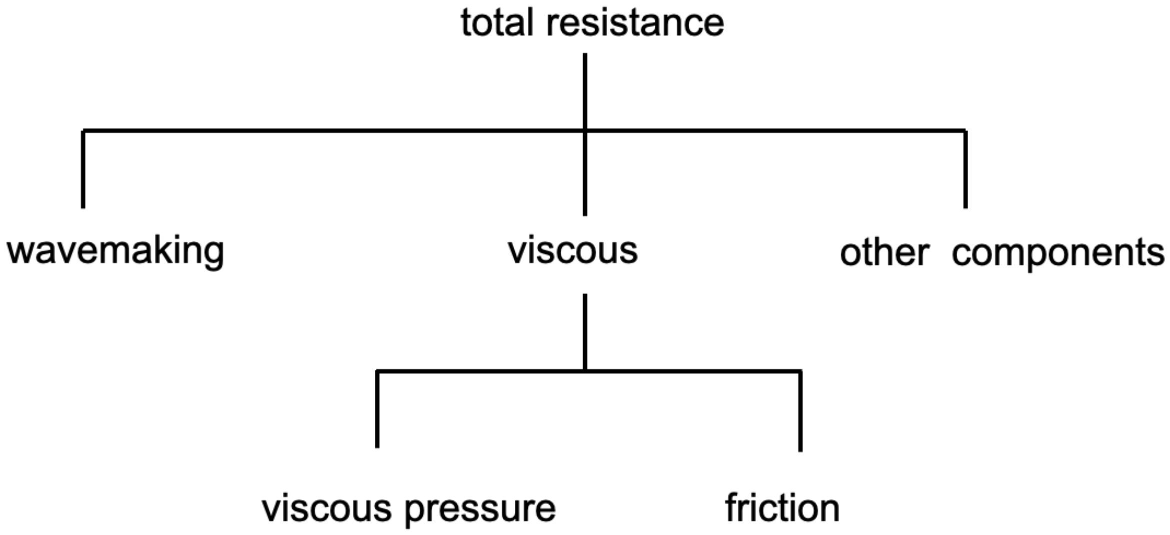
Appendix A: The basic science

This appendix is for those readers who are not familiar with the fluid dynamics of flow over surfaces.

Types of resistance:

Resistance is the force opposing the forward motion of the yacht. It is sometimes called drag (drag and resistance are almost the same thing). The two main components of resistance are wavemaking resistance and viscous resistance. Viscous resistance is further sub-divided into two components: skin friction resistance and viscous pressure resistance. Whilst it is very insightful and convenient to consider each component in isolation, it must be borne in mind that all the components interact with one another. For example, the wavemaking resistance alters the amount of surface area of the hull in contact with the water, thus affecting the friction resistance.

Components of resistance:



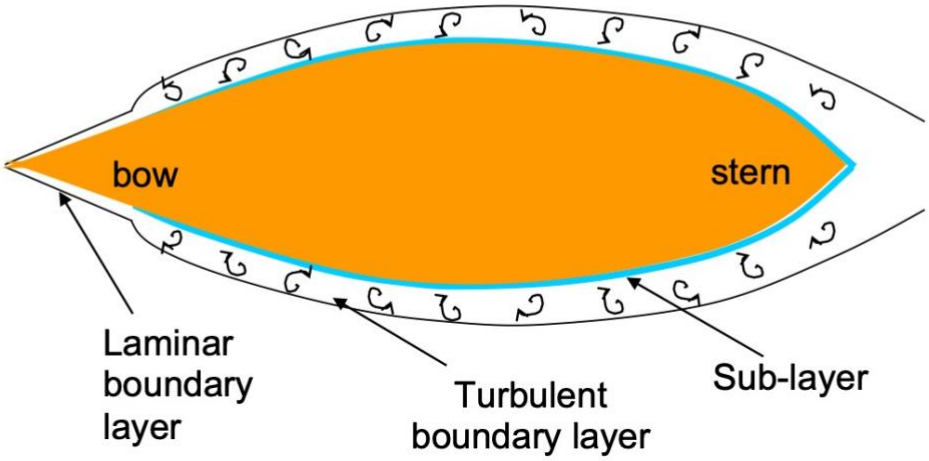
Friction resistance

This is the component of resistance due to the friction between the water and the yacht hull. The amount of frictional resistance is directly proportional to the amount of underwater surface area of the hull – the "wetted surface area". It is this component of resistance which is affected by hull surface roughness.

The boundary layer

When the hull moves through the water, the water particles right next to the hull surface end up being carried along with the yacht. The layer of particles just outside the first layer is also dragged along with the yacht, though not quite so fast. The next layer out is dragged along even less, and so on until at some distance out from the hull, the water particles are not moved at all. The effect is analogous to taking a pack of playing cards and throwing them onto a table. The table is the equivalent of the hull and the cards are the layers of water moving past it. Each card sticks a bit to the next one.

The boundary layer:



Boundary layer thickness exaggerated for clarity

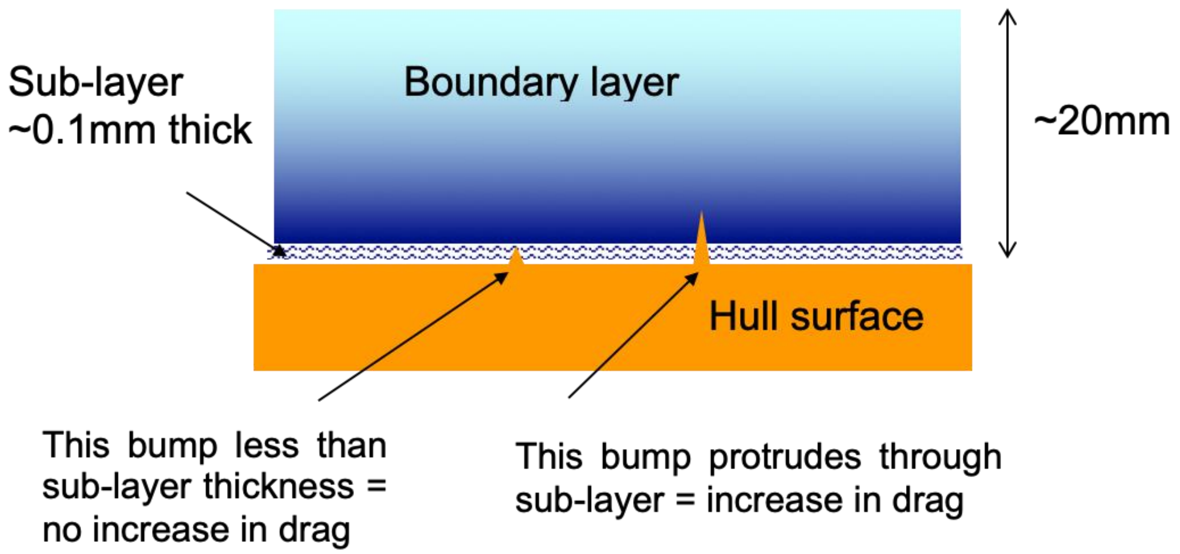
The region of water next to the hull that is affected by the hull moving forwards is called the boundary layer. The boundary layer is quite thin – typically less than 20 mm on a keelboat, and considerably thinner on a model yacht. So it is not readily visible unless you are really looking for it. However, it is this boundary layer of water, and what goes on inside it, that is the key to understanding how the hull surface roughness affects the performance of a yacht. The creation of the boundary layer requires energy. That energy is drawn from the boat by reducing the speed of the boat i.e. the boundary layer creates resistance.

There are broadly speaking two types of flow inside the boundary layer: laminar and turbulent. Laminar flow is when the water particles slip smoothly over one another, rather like the pack of cards do. Turbulent flow is when the water particles are moving around randomly, with layers mixing together and particles crossing each other’s paths. Laminar flow has much less drag than turbulent flow, but it only exists at slow boat speeds, over short distances from the bow. These conditions occur very rarely on a full-size boat, but they are quite likely for the hull of a model yacht. How likely? that is the question that led to the research described in this paper.

The sub-layer

Inside this thin boundary layer of turbulent flow there is an even thinner layer of water, called the sub-layer. The sub-layer is really thin, typically less than 0.1 mm, which is the thickness of a human hair. It is difficult to imagine that this wafer-thin layer of water is so influential on boat speed, but it is. If the roughness of the hull surface is high enough to protrude through the sub-layer, it will cause an increase in frictional drag. The more it protrudes, the greater the friction drag.

The sub-layer:



If the roughness is less than the sub-layer thickness, the hull surface is known as a hydraulically smooth surface; making the surface any smoother will not reduce the drag further no matter how much sanding is done. So for minimum friction drag, if the boundary layer is turbulent then the hull surface roughness should be no higher than the sub-layer thickness. The sub-layer thickness depends on the speed of the yacht and, to a much lesser extent, how far back from the bow it is being measured. As you move aft along the yacht from the bow, so the sub-layer thickness increases. However, at any chosen point on the yacht the sub-layer thickness *decreases* as boat speed increases. So the hull must be smoothest near the bow, and it has to be smoother for high-speed yachts than for low-speed yachts.

All the above is for a boundary layer with turbulent flow. If the boundary layer is laminar, which can occur on a model yacht, conventional fluid dynamics states that roughness will not increase the friction drag. This turns out to be a slight over-simplification.

Separated flow

There is a third type of boundary flow, called separated flow. As the name implies, it occurs when the entire boundary layer separates away from the hull, leaving a void to be filled with eddies or swirls. Separated flow can occur with both laminar and turbulent flow boundary layers. It is usually visible at the stern of the boat in the form of the wake (the eddies and swirls created by the separated boundary layer.) Separated flow is triggered by the curvature of the surface causing an adverse pressure gradient pushing against the boundary layer, "peeling" it off the hull. The extra drag (resistance) created by separated flow is a component of viscous pressure resistance, not friction resistance. Separated flow is influenced by surface roughness, but not in a generalised or readily quantifiable way. It will not be considered further here.

Reynolds Number

Readers might be familiar with the Mach number, which is used to described whether an aircraft is flying faster or slower than the speed of sound. There is a similar type of number, called the Reynolds number, that describes the type of flow over the surface of the hull. Scientifically, it is the ratio of inertial forces to viscous forces. For a yacht hull it can be approximated mathematically as:

Reynolds number = boat speed (kn) x distance along the hull (m) x 1.7 x $10^{6.}$

This means that, if the hull is very long, or if it is travelling very fast, then the Reynolds number is large and the viscous forces are less important than the other forces (e.g. wavemaking resistance). The Reynolds number also turns out to be an indicator of whether there is likely to be turbulent flow or laminar flow in the boundary layer. Indeed, for a smooth surface with no pressure gradient, there is a specific Reynolds number, called the critical Reynolds number, beyond which laminar flow cannot exist (about 1 x 10^6). The value of the Reynolds number also determines how thick the boundary layer is, how thick the sub-layer is, and lots of other boundary layer characteristics.

Appendix B: surface roughness effects on foils

The fin and rudder of a typical model yacht of waterline length 1m operate at Reynolds numbers from about 2×10^4 to 1×10^5.

Thin foils at zero inflow angle have low pressure gradients, so they are likely to be operating in laminar flow owing to their chord length being an order of magnitude smaller than the hull length. However, for thicker foils or for foils operating at some inflow angle, the pressure gradient probably determines the likelihood and extent of laminar flow.

Zero inflow angle

For zero inflow angle the foils can be treated as for the hull. The assumption of zero pressure gradient is clearly false over most of the foil surface. However, it is favourable to retaining laminar flow near the nose, and for laminar flow sections at least, it remains favourable for some way back – perhaps 60% of chord length. The nature and extent of laminar flow over the rear half of the foil is strongly dependent on the section used. So treating the foil in the same way as the hull (i.e. flat plate with no pressure gradient) gives estimates of the transition point that are valid only if transition occurs well aft; otherwise the results are of questionable validity.

Angle to flow

At typical leeway angles when sailing to windward, can there be laminar flow over the foils? The foils operate at a lift coefficient of between 0.2 and 0.4 when sailing to windward, shown in Table 9.

DF95	**keel**	**rudder**
span (mm)	300	150
chord (mm)	70	45
AR_G	4.29	3.33
AR_E	7.29	5.67
C_L @3°	0.233	0.215
C_L @5°	0.388	0.359

Table 9: Operating upwind lift coefficients

Hoerner Ch2-12 states that for a smooth 65-series section (i.e. a “laminar flow” section), for a lift coefficient higher than about 0.1 to 0.2, “the flow around the leading edge disturbs the boundary layer so that it turns turbulent shortly aft of the leading edge”. This is the standard explanation for the bucket shape in the lift v drag curve and is in keeping with the results shown in Hoerner (ch 2-12, fig 17). However, those results are at a Reynolds number of 6×10^6; they might be quite different at lower Reynolds numbers. The general view is that the lift coefficient for bucket sections on a model yacht foil should be kept below about 0.3 (Bantock, 2021).

The flow regime is further complicated by the possibility of a laminar separation bubble near the leading edge. Simons (1978) states (p27) that separation bubbles rarely occur on full size aircraft but they do occur on model aircraft wings. Full size aircraft usually operate above Reynolds numbers of 10^6 whereas model aircraft operate at Reynolds numbers of around 10^5, putting them in the same flow regime as model yacht foils.

Conclusions

- The foils are operating in laminar flow unless the leading edge or environmental turbulence trips it.
- There is a strong chance of a laminar separation bubble on the foils when sailing to windward. This detracts from performance. It may be worth trying to artificially turbulate the flow over the foils.

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