

Hull-Sailplan balance, “lead” for the 21st Century.

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Introduction.

Up until the relatively recent past much of the design of sailing yachts has been codified with fairly reliable “rules of thumb”¹. These were helpful whilst sailing yachts were traditionally constructed with fixed ballasted keels and “normal” underwater profiles and sail plans. In the last 20 years this has changed with the advent of canting keels, lightweight construction techniques and novel rigs. Also sailing yachts are getting larger (100m +) and different ratio’s of length to draft are in play. The fundamental importance of correctly positioning the rig in the boat has not diminished, but it has certainly become much harder to do reliably using empirical methods.

Traditionally placing the mast and sails in the correct longitudinal position on the hull and keel was done by positioning the centroid of the sail plan a prescribed distance forward of the centroid of the immersed profile of the hull keel and rudder,[Figure 1]. In such a way the sail plan centre of effort (CE) was given a “lead” over the hull centre of lateral resistance (CLR). These rules of thumb, that varied with hull type, were quite reliable as a way of capturing “good practice”, i.e. if you copied the “lead” of a well balanced boat for a new design there was some prospect of achieving satisfactory helm balance.

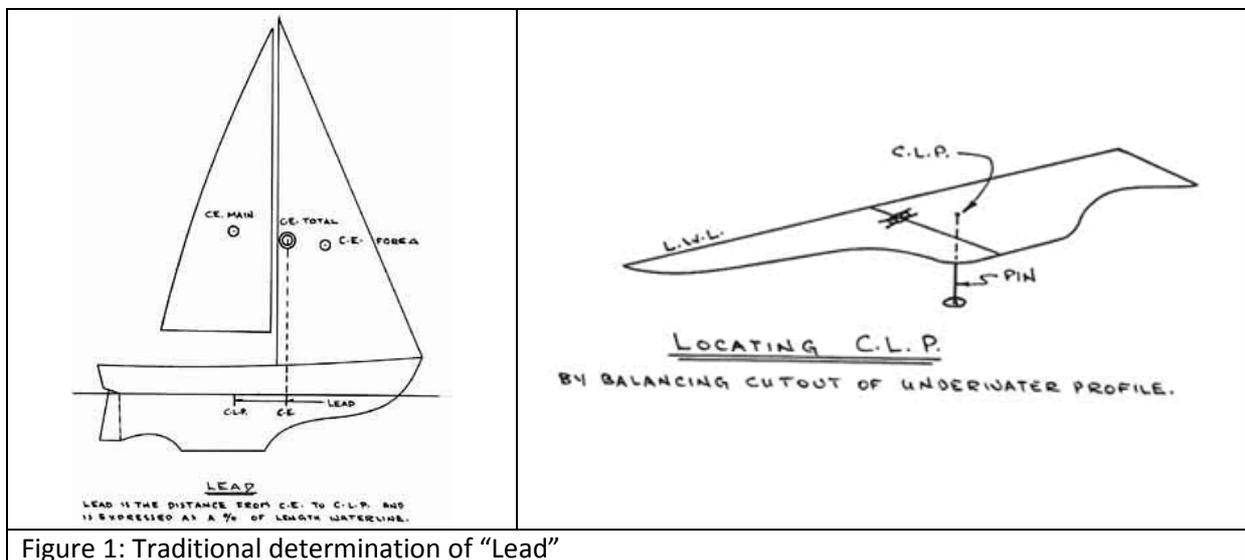


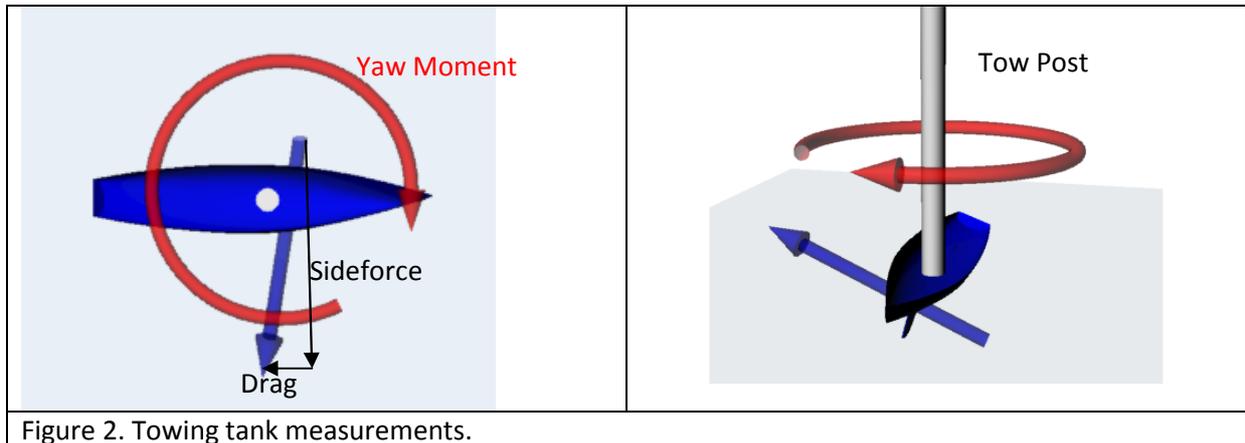
Figure 1: Traditional determination of “Lead”

I think it is safe to acknowledge that the centroid of area does not really approximate to the CLR or CE, if indeed we can find these.

¹ The origin of the phrase remains unknown. It is likely that it refers to one of the numerous ways that thumbs have been used to estimate things - judging the alignment or distance of an object by holding the thumb in one's eye-line, the temperature of brews of beer, measurement of an inch from the joint to the nail to the tip, or across the thumb, etc. The Germans have a similar phrase to indicate a rough approximation - 'pi mal daumen' which translates as 'pi [3.14...] times thumb'.

Force Equilibrium for a sailing yacht.

When I started out at the Wolfson Unit we naturally tried to move the science forward from balancing cut outs of the sail plan or hull on a pin. In the towing tank with tests on a restrained model we measure the drag and sideforce components of the total hydrodynamic force and the yaw moment generated by the model. We can analyse the data to determine the CLR, that is the intersection of the line of action of the total hydrodynamic force with the centre plane (mast plane) of the yacht (Figure 2).



We can then look to predict the complete force balance for the sailing yacht. Note that the total force vectors have only a magnitude and a line of action, the much talked about CLR and CE are only meaningful as the intersection of the line of action with the centreplane of the yacht, or any other chosen plane.

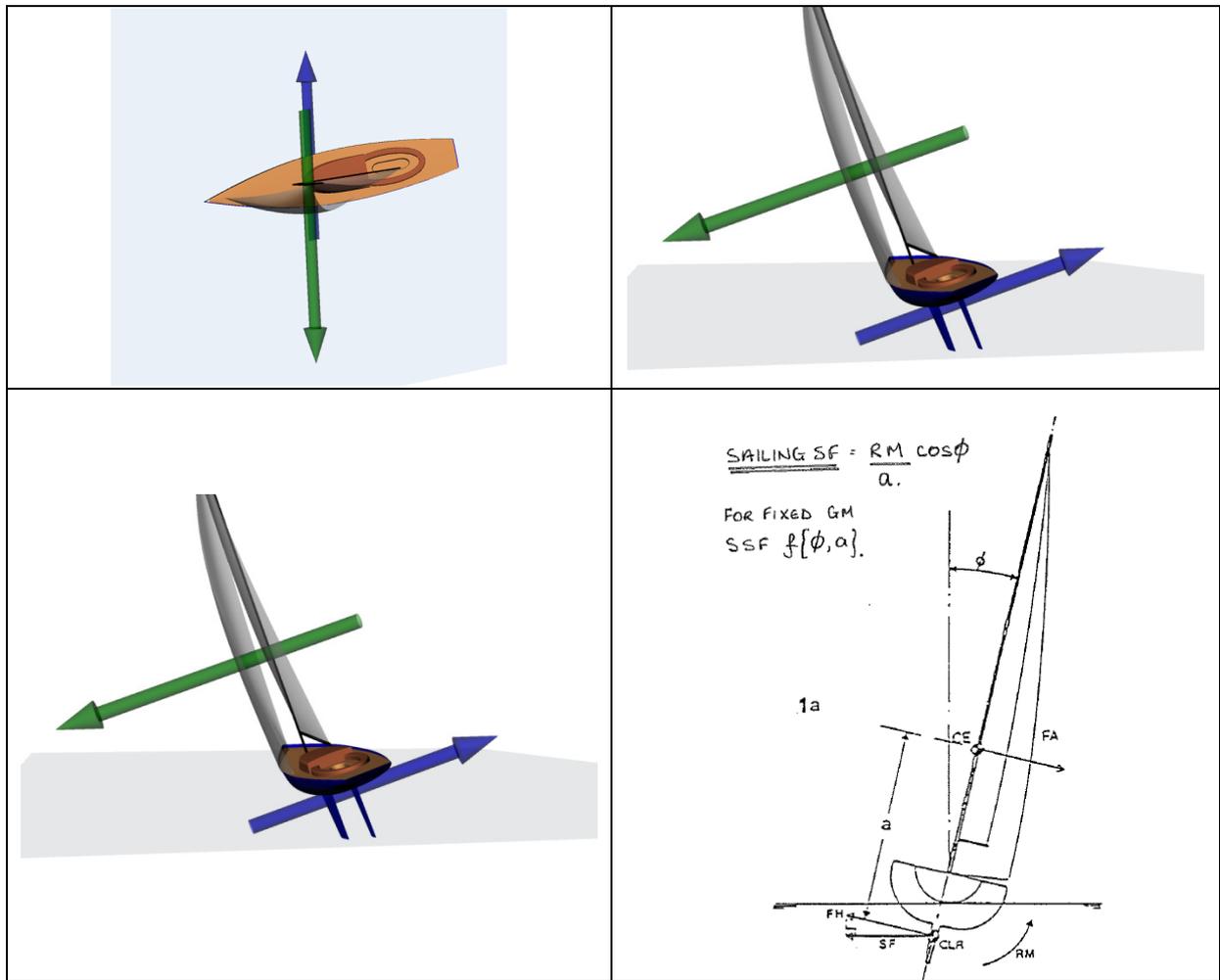


Figure 3. Overall Sailing Yacht Force Balance

The aerodynamic and hydrodynamic forces are equal and opposite in direction, and their couple is equal to the righting moment at the sailing heel angle. A key factor in this balance is that if the righting moment and the separation of the CE and CLR are known then the equilibrium "Sailing Sideforce" is completely defined. This is of particular relevance to the understanding of how yaw moment equilibrium between the hull and sails is established.

The Centre of Lateral Resistance (CLR) that is the intersection of the line of action of the total hydrodynamic force vector with the centreplane of the yacht. In a towing tank test typically the following types of behaviour are observed, which are largely dependant on hull type. Figure 4 shows the longitudinal CLR position plotted against the measured sideforce. Each data point is derived by towing the model at a fixed speed and heel angle and in subsequent runs increasing the leeway (drift) angle so that sideforce increases.

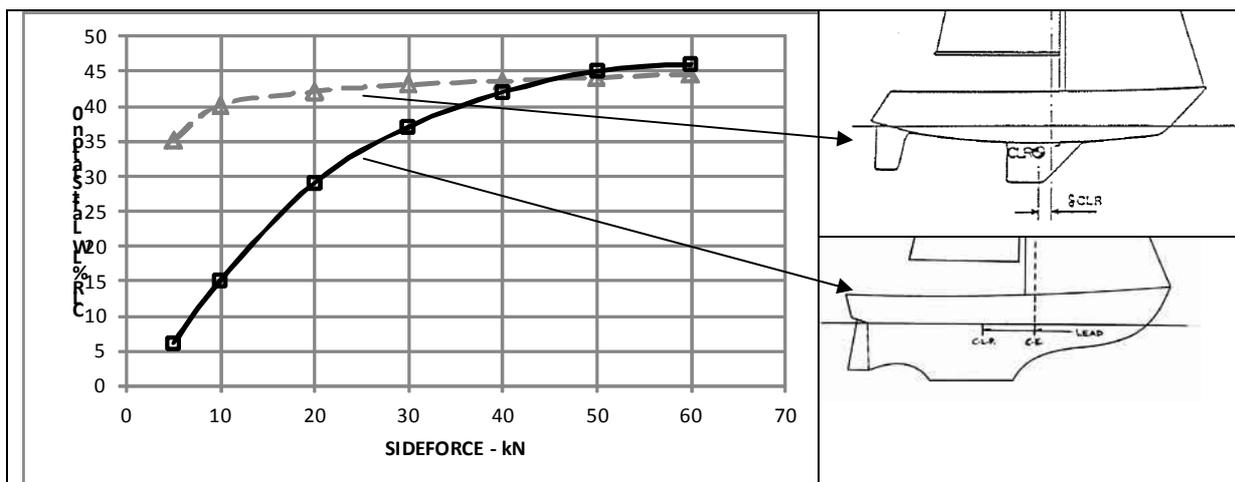


Figure 4. Typical CLR vs. Sideforce data plot, fixed speed and heel angle.
Fin Keel and long keel yacht types.

Note that the deep keel and rudder take the greater proportion of the lift generation, and hold the CLR aft even at low leeway angles, the shallow draft yacht by contrast has lift divided more evenly between hull and keel, and the greater contribution from the hull and its associated "Munk" moment holds the CLR forward at lower sideforce values. As the leeway and sideforce increase the keel forces dominate the hull forces and pull the CLR aft. Thus the shape of the CLR vs Sideforce curves are related to the hull and keel shape, but the actual sideforce at which the yacht sails are determined by the hull righting arm curve, the stiffer the yacht the higher the equilibrium sideforce. (Figure 3)

As shown in Figure 3, for the boat to sail the two force vectors must be aligned, i.e. the CLR and CE are the same distance aft of the bow, no lead or lag etc.

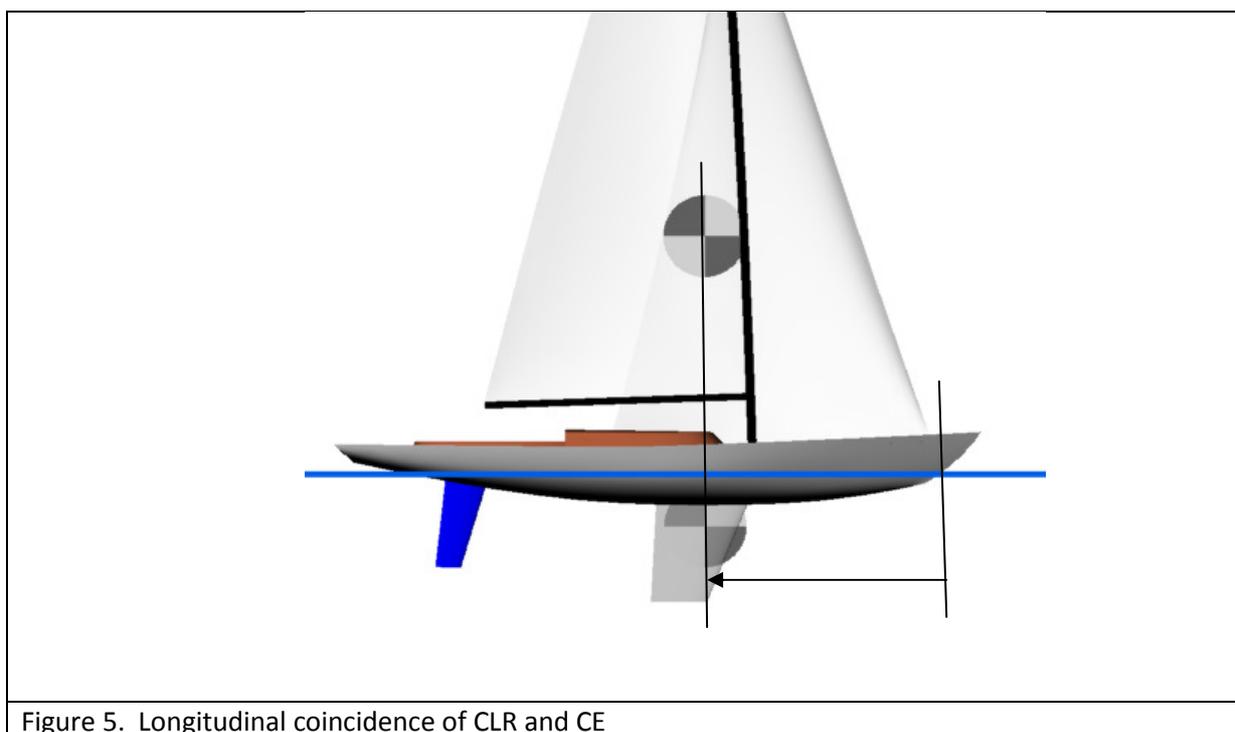


Figure 5. Longitudinal coincidence of CLR and CE

A Lesson Learned

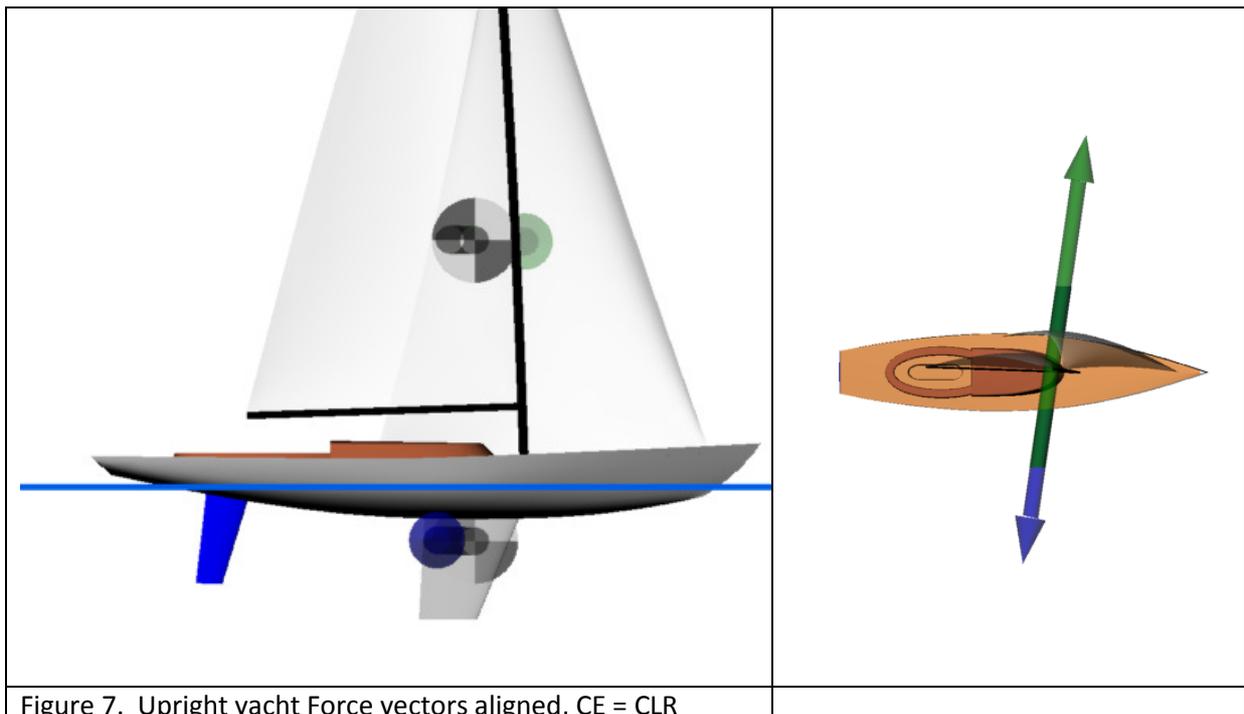
As a young engineer I was aware of all this, and ready to apply my science. One of the first yacht tests I ran was for Rossiter Yachts on their new “Curlew” design. The family firm who built the boat knew that the combination of shallow keel, deep canoe body and small rudder made the correct positioning of the rig essential for good sailing performance, and ease of handling.



I did the tests and determined the CLR, made an allowance for the sailing rudder angle. I calculated a sail plan CE that was based on the $\frac{1}{4}$ chord of the sails so that an actual CE position could be used. This is somewhat different of course from the centroid of the sail area. Notions of lead must be abandoned at this point, we are no longer in “rule of thumb” territory, science is in charge.

I carefully placed my CE in line with the CLR, and said “put the mast here”.

Nothing was heard for 12 months whilst the boat was built, but then the designer came back with tales of terrible weather helm, what mistakes had I made? It turns out I had failed to take one last and vital step. Figure 7 shows alignment of the CLR and CE, and the view from above the yacht shows coincidence of the lines of action of the aero and hydrodynamic forces.



However if the yacht is now heeled, without changing the location of the CLR and CE , as shown in Figure 8, the force vectors are no longer co-linear, and for equilibrium to be restored weather helm must be applied to pull the hydrodynamic force aft

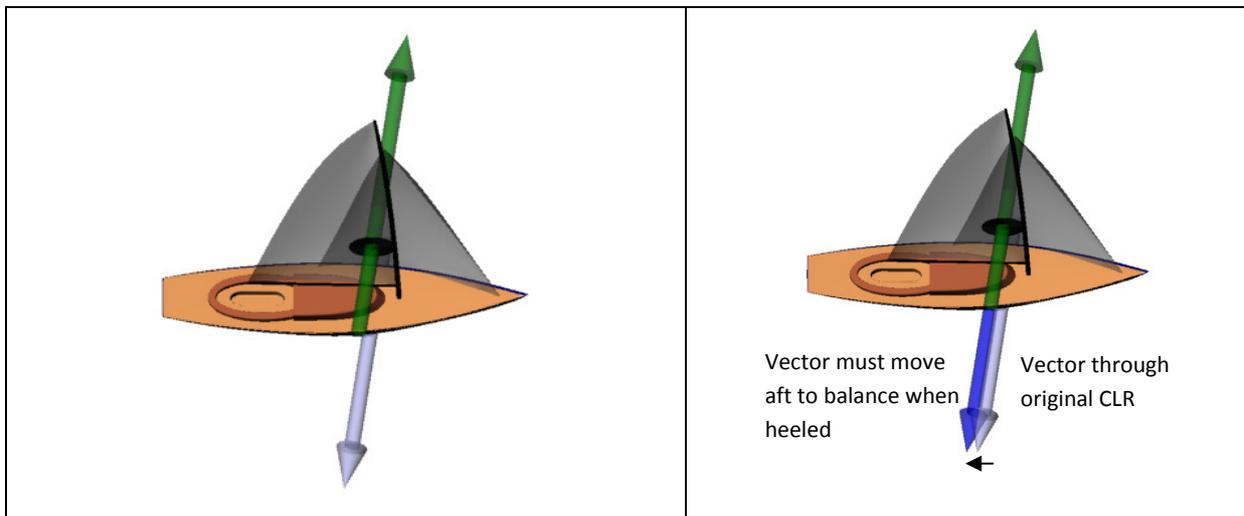


Figure 8: Misalignment of the aero and hydro force vectors due to heel alone.

In the heeled condition longitudinal coincidence of CLR and CE does not lead to a zero net yaw moment, the CLR must be corrected before it can be matched to a CE . The shift does not look very much, but it is there.

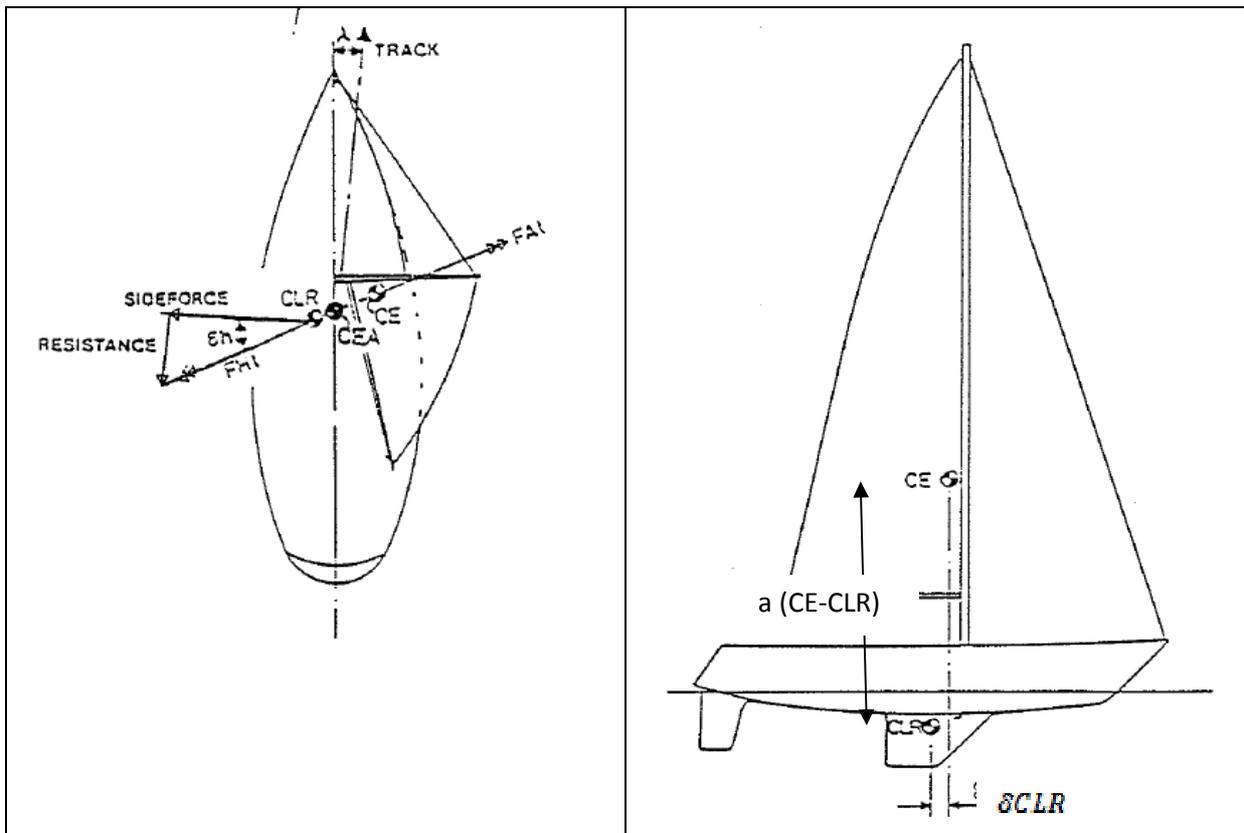
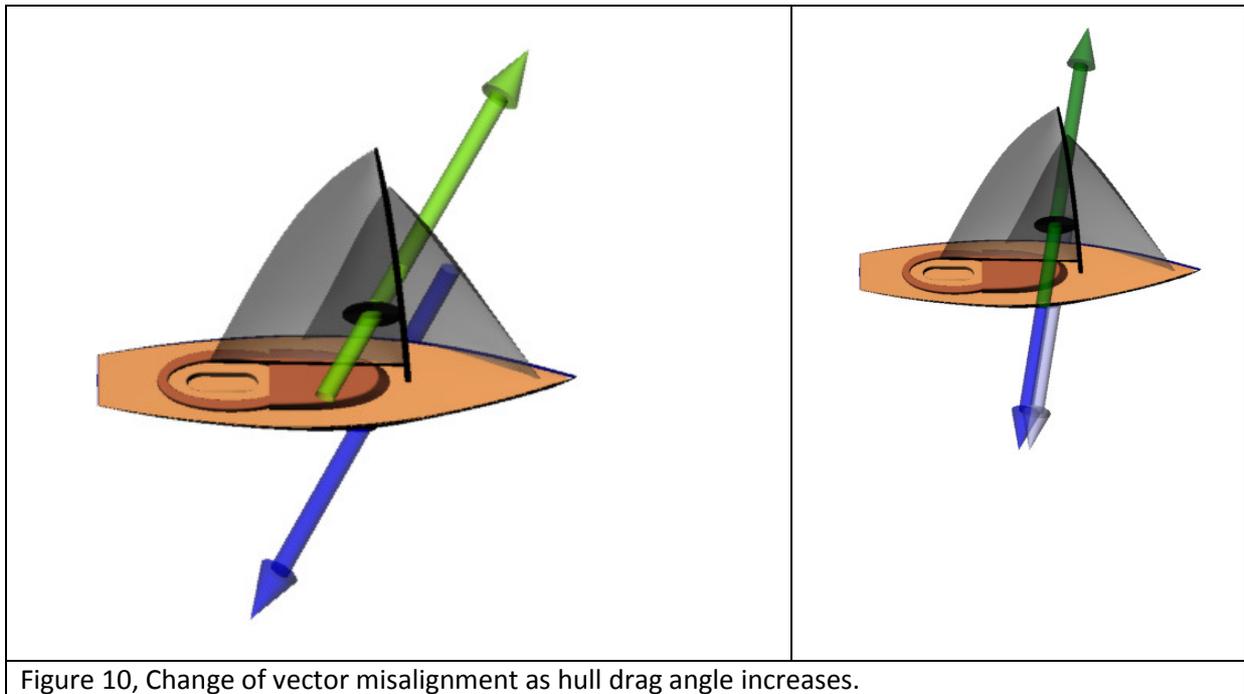


Figure 9. Calculation of CLR shift (δCLR) to match CE and CLR when heeled.

$$\delta CLR = \frac{a \cdot \sin \varphi}{\tan (90 - \epsilon h)}$$

Now the source of my earlier error is clear, the balance of the hull and sail forces is affected by the the line of action of the hydrodynamic force, i.e. the hydrodynamic drag angle, (ATAN (Drag/Sideforce)).

Consider now the situation shown in Figure 10, here the hydrodynamic force vector is pointing more aft, i.e. the hull drag is increased, and now, whilst the CLR and CE are identical to those in Figure 7 the misalignment of the two vectors is much greater, requiring more weather helm to move the hydrodynamic vector aft and into line with the aerodynamic forces.



This is the final piece of the “Curlew” jigsaw. The out of balance arm as the yacht heels (δCLR), without altering the rudder, is dependant on the drag angle of the hull and appendages, i.e. the resistance to sideforce ratio. If the boat has a low sailing sideforce, i.e. it is tender, and has a high drag the vector misalignment induced by heeling is much higher than for a hull with a low drag angle. The “Curlew” had conspired to have the highest possible drag angle, it had 3 keels, and shallow draft, and it was a relatively tender boat, i.e. it had a low sailing sideforce. Thus at 20 degrees of heel the out of balance moment is high, and large rudder angles are needed to pull the hydrodynamic line of action aft, i.e. the rudder must take a greater share of the sideforce. A further complicating factor is that the rudder was small, so of course it needed even more weather helm than if a more normal rudder area could have been chosen.

Munk Moment

To add to the problem of establishing the CLR of a yacht, the hull can have a larger influence on yaw moment than it does on side force. The heeled hull form of most yachts is relatively long and thin, and as such, when operating at an angle of yaw to a flow, the body will generate what is known as a Munk Moment. The pressure distribution over the body, as shown in Figure 11, gives rise to a small or almost zero side force, as the force generated at the bow is cancelled with the force generated at the stern. There is however a net moment generated, which due to the long lever arms of the pressure difference, can be significant. The Munk moment [1] is a destabilising moment, as it causes the angle of attack to the flow to increase, thereby increasing the moment further.

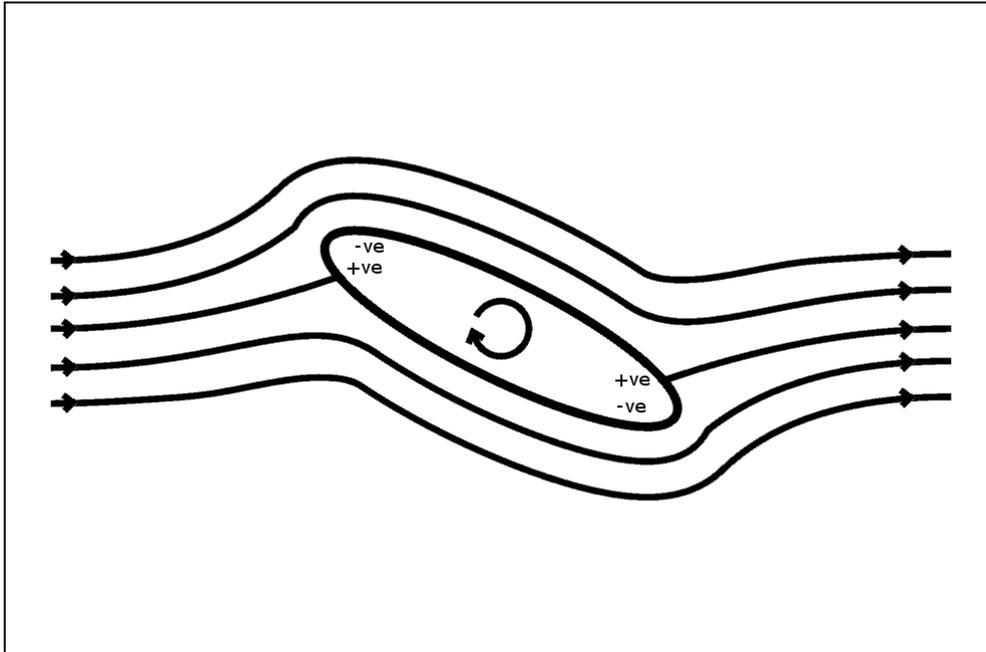


Fig 11: Streamlines around a slender body, generating a Munk Moment.

For submarines, the Munk moment can be potentially dangerous, which is why they are fitted with stabilising fins.

Figure 12 shows the pressure distribution calculated on an un-appended large super yacht hull form using a VOF free surface RANS simulation in Open FOAM. The hull is operating at an angle of leeway of 6 degrees and a F_n of 0.245. In this configuration, the lift coefficient (C_L) for the hull is 0.0012, and if we were to assume this side force had a centre of effort at 25% of the LWL aft of the bow, the yaw moment coefficient (C_m) would be 0.000292. This however is not the case, the actual C_m is almost 10 times larger at 0.0023. This highlights the potential difficulty when making a balance calculation based on weighted areas of the hull due to their sideforce contribution.

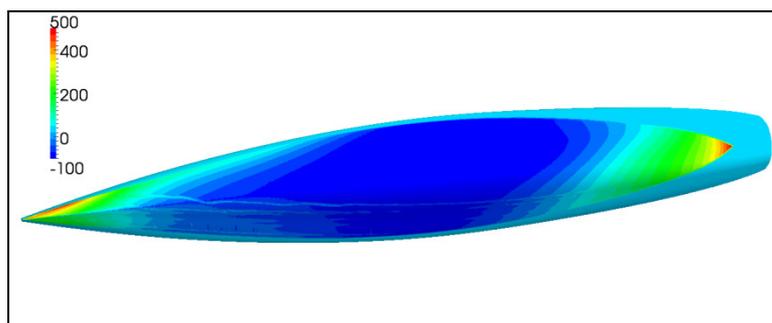


Figure. 12 A superyacht hull form and the pressure distribution.

Figure 13 shows the pressure distribution in the same condition along a waterline, along with the net local side force contribution along the length of the hull. The difference in sign between the bow region and stern region can be seen, along with the negligible contribution from the middle of the hull form.

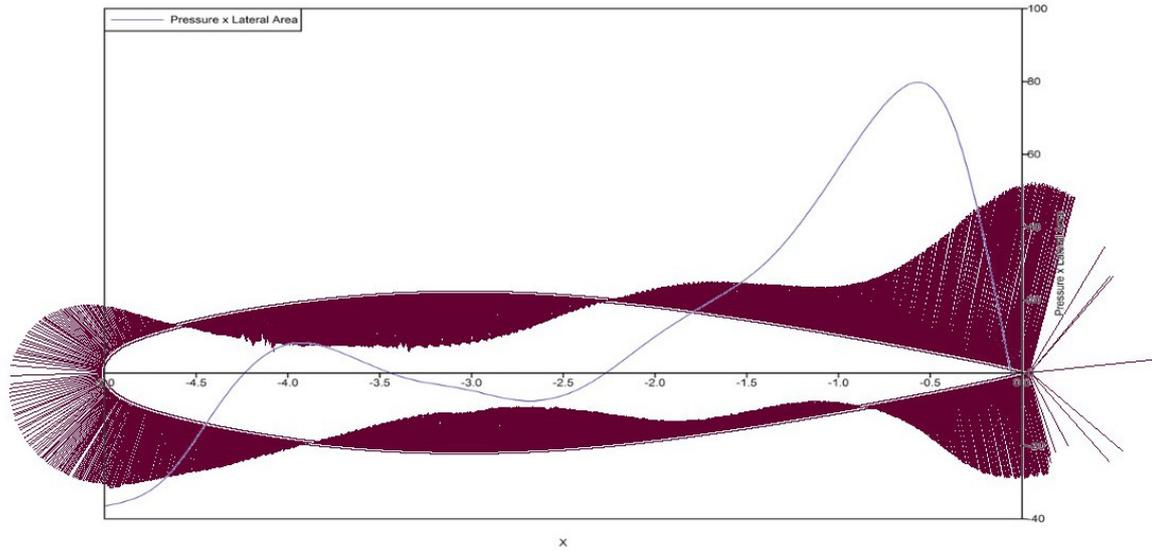


Figure. 13 The pressure distribution around the same hull form along a water line just below the static waterline, with the net side force contribution along the length of the hull.

Practical Considerations.

These are the main players in the game of achieving good helm balance, based on this what should a designer consider in order to achieve good helm balance.

Race boat versus Super-yacht

There are fundamental design difference between a typical race boat and super-yacht which has a large impact on rudder use and effectiveness.

Raceboat

- Reasonable keel draft and high lift (SF) generation, coupled with high Sailing Sideforce
- Reasonable rudder draft and high potential lift (SF) generation on the rudder
- Shallow light displacement hull which has minimal contribution to overall lift (SF) production
- Low drag, high sideforce, therefore low drag angle

Superyacht

- Draft restricted keel, low aspect ratio
- Draft restricted rudder, therefore limits on rudder area
- Keel downwash effects on rudder
- Deep, moderate to high displacement hull with significant lift (SF) contribution
- Strong Munk moment contribution
- Higher drag, low sideforce, therefore high drag angle

The result is that the steady state sailing rudder angles (across a large range of speed and heeled conditions) for the raceboat will be within a small range, typically 2° to 5° weather helm, whereas for a superyacht it would typically be $(-2^\circ$ to $10^\circ)$, lee-helm to excessive weather helm. This is a primary reason to test a cruising yacht hull, whilst resistance can be calculated with some accuracy, the detailed mapping of CLR with speed and heel angle is vital in ensuring good helm balance.

Rig Sloop vs. Ketch

Although the hull righting moment, side force and drag set the alignment of the force vector that the aerodynamic forces must match, the aerodynamic Centre of Effort can be controlled by trimming the sails to maintain balance.

Sloop rigs offer marginal variation in what we would term longitudinal centre of effort (CEA). As the yacht becomes overpowered, so the mainsail is flattened and twisted in order to reduce the heeling moment. This results in an overall lowering of the centre of effort height and a longitudinal CE shift forwards (ignoring heel effects), this shift is typically of the order of 6 % of LWL at a constant apparent wind angle.

For a ketch this range can be far greater, of the order of 10%. This is due to the large lever created when easing the mizzen in relation to the other sails. This is not a solution to an incorrectly longitudinally located sailplan but gives greater potential for balance harmony with regards to providing manageable rudder angles and positive lift production across a large range of sailing heel angles and speed. In the case of a yacht where sail sheeting adjustments are necessary to maintain balance, this will have an effect of aerodynamic performance and therefore boat speed. The yacht with good balance between the hydrodynamic and aerodynamic components can be pushed to its potential, but a yacht that will not balance has no potential.

This is the essence of the tuning process, finding sail trims that have good aerodynamic efficiency, whilst maintaining hydrodynamically optimum rudder angles. Additionally, the tuning process is to do with finding ways to lower the CE when the boat is overpowered. If CE can be lowered then the equilibrium "sailing sideforce" is increased (at a fixed heel angle), and if you can support a higher heeling force, a higher driving force is almost guaranteed.

Multiple Appendages

Yachts with multiple appendages bring in other complications (even though their drag angle is low), depending on the appendages deployed the CLR may be shifted large distances. As in the case of an Open 60, this can be sailed with a vertical or canted keel and with a dagger-board. Open 60's are a special case as their heeled waterlines are highly asymmetric and therefore have a noticeable effect on CLR and drag.

The effect of the dagger-board (usually asymmetric) reduces the lift of the hull by reducing leeway and takes a large proportion of the overall lift. To accommodate this, the Open 60's position the dagger-boards to minimise their impact longitudinally, have reasonably large and effective rudders, and versatility in the sails that can be set to maintain balance.

Single/Twin Rudders

There are also distinct differences in the properties of single and twin rudders. Single rudders operate in the downwash of the keel ahead of them. This downwash is a function of rudder - keel separation and aspect ratio of the keel. This has the effect of lowering the local angle of incidence and local flow speed in way of the rudder. This reduces the rudder force over that in the free stream condition as you have with a twin rudder option.

The twin rudders also benefit from the dihedral angle making the leeward rudder more vertical, therefore its lift contribution is more in line with the waterplane and for the Open style boats, with wide transoms, it is often possible to get a majority of windward rudder clear of the water.

Twin rudders allow more area to be accommodated in restricted draft conditions, they

- Move the rudder out of downwash from keel
- Get more rudder area
- Have a larger shift of CLR per degree of rudder angle compared to single rudder

Establishing Forces and Moments

Clearly in yachts with multiple, adjustable, appendages there is a need to know the force contribution from each component so that the overall hydrodynamic force vector can be determined. The new Windesign 6 VPP has a fully “component” based structure so that force models for each appendage can be accommodated, and local incidence angles determined. For wing like appendages this approach works well, but the force modelling for the canoe body is more complex.

The development in computer processor power has allowed institutions to build large scale high performance computing facilities far more cost effectively than was possible even 10 years ago. The University of Southampton’s super computer, Iridis 3, has approximately 12000 processors and is capable of providing over 72 TFlops². Coupled with the growth in open source software, users have been able to take full advantage of large machines without the expensive overhead of licenses for such computers.

The Wolfson Unit MTIA have been using the openFOAM CFD package on Iridis 3 to calculate both Reynolds Averaged Navier Stokes (RANS) Simulations and Detached Eddy Simulations since 2010. The large computer power has decreased the solution time and allowed for a higher level of discretisation³, thus improving the accuracy of the solution compared to a simulation which was made 10 years ago.

CFD has a role to play in assisting designers with balance calculations, as there is a great benefit to be had in evaluating preliminary configurations of both appendages and sail plans with a higher level of confidence than relying solely on empirical data. The forces and moments calculated by the CFD can then be used within the VPP to establish the balance characteristics of the yacht. Rather than competing with the experimental route, the numerical tools allow for a more informed experimental programme. The computer provides insights, the experiments hard data.

CONCLUSION.

This paper has been an attempt to de-mystify the force balance in play when a mast and sails are used to propel a hull and keel. The physical mechanisms are simple, and the main effects can be quantified quite readily with current design tools. The key is to understand the fundamental interlinking of the righting moment and the centre of effort height in fixing the equilibrium sideforce at each heel angle. (Figure 3), and how having a relatively low or high sailing sideforce affects the CLR position. (Figure 4). Additionally the hydrodynamic drag angle affects how the aero and hydro

² 72 x 10¹² Floating Point Operations per second

³ Larger Meshes > 20 x 10⁶ Cells

forces move out of alignment as the boat heels (Figure 10). The traditional heavy yacht with high wetted surface and low sailing sideforce has a high drag angle and requires weather helm as the boat heels to hold a steady course, also the full hull shape attracts a high Munk Moment. At the other end of the spectrum, say a catamaran, the drag angle is low, the sideforce high, and Munk Moment negligible, consequently, next to no weather helm is generated as the boat heels.

References

[1] M. Munk, N.A.C.A. Report No. 184 (1924)