To Twist, or Not to Twist? — A Scientific Attempt to Understand What We Think We Already Know About Sail Trim

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ABSTRACT

The impact of mainsail sheet tension and traveler position on performance has been investigated, particularly under conditions when it is necessary to reduce power. Photographs of the mainsail on a Beneteau First 36.7 under various trim conditions were taken and analyzed to determine sail shape. The resulting shapes were used to create a CFD model, and the aerodynamics forces on the sail plan were determined. The results strongly suggest that for this boat it is more efficient to reduce power by keeping the main sheeted hard and lowering the traveler than by keeping the traveler up and easing the sheet, although a small amount of sheet easing is beneficial. The lift distributions for all sail trim combinations investigated are underloaded near the masthead relative to an elliptic distribution, which means that any additional twist in the main increases the induced drag. The difference in performance is almost entirely attributable to differences in the induced drag.

NOTATION

AP all-purpose jib (150% overlap)
AWA apparent wind angle
C.E. Center of effort
CFD computational fluid dynamics
Di induced drag
IMS international measurement system
k turbulent kinetic energy
V far-field apparent wind velocity
VPP velocity prediction program
y elevation from the water surface
ε turbulent rate of dissipation

INTRODUCTION

An experienced sailor can usually get almost any boat sailing well using rules of thumb; however, this isn't enough when racing in a competitive fleet. It takes a great deal of time on the water to get the most out of a boat, and it is necessary to experiment with sail trim, crew position, and steering technique. Racing certainly provides an opportunity to fine-tune performance, but tuning is complicated by tactics and strategy necessary to deal with other boats. Boat-for-boat tuning is the best way to determine what halyard and sheet tensions should be for a given condition, but this is also a very time consuming process. For this reason it is important to understand the physics of performance (especially sail trim), for such knowledge can be a guide in terms of knowing what to change and how it will affect speed.

Theories on the nuances of sail trim abound, and discussions both on and off a boat can be quite lively about what the fastest setting is and why. Due to the complexity of sail aerodynamics, many of the phenomena that affect performance are not well understood, and in some cases commonly accepted ideas — for example, the notion that the air is moving fastest in the slot between the main and the jib — are just plain wrong.

A question of particular interest to the authors is the following: when sailing in conditions where it is necessary to begin depowering, is it better to keep the main sheeted hard and lower the traveler, or is it better to keep the traveler up and ease the sheet? The fundamental trade-off in this question is that easing the sheet (and thus twisting the main) lowers the center of effort of the sail plan, allowing more driving for a given heeling moment, whereas keeping the sheet tight maintains a more elliptical spanwise lift distribution, which keeps the induced drag low. Previous research (Wood and Tan, 1978) has shown that in these conditions it is better to lower the center of effort and have a non-elliptical lift distribution; in fact, for very tall rigs it has been shown that the optimum sail trim has a negative lift distribution near the masthead. One of the present authors, who sails a Beneteau First 36.7, was told by the sailmaker that it is better to depower by twisting the main than by dropping the traveler, primarily due the fact that the 36.7 has a fractional rig (in theory keeping the main sheeted will cause the top of the main to stall). Experience also suggests that a boat with a twisted main is easier to drive than a boat with the main sheeted hard, and this may be a factor in performance.

Discussions with other sailors on this question have resulted in split opinions and a wide variety of theories as to why their opinion is correct. To better understand what
is happening from an aerodynamic viewpoint, a project was undertaken to assess the effect of twist vs. dropping the traveler on the 15/16 fractionally rigged Beneteau 36.7 in conditions which are marginal for carrying a #1 jib (an all-purpose, or AP overlapping jib on the 36.7). While it is recognized that there are other ways to depower (for example, moving the jib lead aft), it was necessary to focus on this one question – other issues can be investigated in future research.

In the present work the boat was sailed with an AP jib and a full main in wind speeds close to maximum for that configuration. Photographs of the mainsail were taken for various sheet and traveler positions, and a CFD (Computational Fluid Dynamics) model of the sails was built to determine the forces and moments on the sails. The results were analyzed to answer the question as to which configuration is better, and why.

PROCEDURE

Sail Photography

Simple photogrammetry was used to estimate the actual flying shapes of the mainsail under various settings so that these shapes could be used for later analysis. The boat was set up for conditions where the wind speed was close to maximum for the AP and full main. The actual maximum wind speed for this configuration is in the range of 15-17 knots true, whereas the tests were performed in 12-14 knots true. This lower wind speed was used to make boat handling, sail trim, and photography easier. While the measured shapes may not be those exactly seen in depowering conditions, they do provide a family of realistic shapes that can be used to assess the impact of mainsheet tension and traveler position on performance. The halyard and rig tensions were set at values appropriate for the conditions. The AP jib lead was in its normal position for moderate to heavy air.

An Olympus D-550 3 MP digital camera was used to photograph the upper portion of the main from a position under the center of the boom. A Kodak PlaySport™ ZX3 High-Definition digital video camera was mounted at the masthead, pointing down at the center of the boom. This camera provided two hours of recording, which was more than adequate to obtain the necessary images. A hand-held digital audio recorder was used to record sail settings, photograph number, and clock times, and these were correlated with images from the video camera. Frames were extracted from the video at the appropriate times. The AP jib was photographed from the deck only. Photographs were taken from several locations on the deck to estimate the draft, lead position, and twist.

The boat was sailed upwind with both telltales on the jib streaming aft, which produces a tacking angle of approximately 80º (40º true wind angle). The main was sheeted so that the boom was on centerline and the aft end of the upper batten was parallel to the boom; this will be referred to as the “base setting.” The traveler was lowered in increments of approximately 6” until the main started to flog. At this point the sheet was eased approximately 9” (corresponding to an actual ease of 1.5” based on a 6:1 mainsheet purchase), the boom was re-centered, and the traveler was again lowered in 6” increments until the main flogged. This process was repeated until it was not possible to ease the main sheet any more without the main flogging.

Analysis of photography

The photographs taken from the deck allowed for the determination of the shape and twist of the main at the three draft stripes. UK AccuMeasure™ software (which can be downloaded for free) was used for these measurements. An example of the output is shown in Figure 1:

![Figure 1 – typical output from UK AccuMeasure™ software.](image)

The user drags a curve over each of the draft stripes, matching the shape as closely as possible. For each section the software computes the amount and location of maximum camber as a percentage of chord length, the amount of camber at 15% and 75% of chord from the luff, and the angle of twist relative to the photograph horizontal.

The photographs taken from the video camera at the top of the mast were also analyzed using the software; however, due to a relatively low resolution, the position of the camera, and the appearance of the “backwind bubble” at the luff, it was not possible to accurately determine the section shape. These photographs (see example in Figure 2) were therefore used to determine only the angle of the boom relative to the centerline of the boat, and the angle of twist of the upper draft stripe relative to the boom, neither of which could be accurately measured from the deck.
Figure 2 – typical photograph taken from the top of the mast. Note that due to the backwind bubble it is impossible to see all of the lower two draft stripes.

With the information taken from the two photographs for each sail setting, it was possible to determine the location of the boom and the shape and twist at each draft stripe relative to the boom. A summary of the sail shapes that were analyzed is provided in Table 1. Each sail setting is coded as follows: the first number provides the boom position relative to centerline, the second is the amount the sheet is eased from baseline, both in inches. For example, 0-0 is baseline (boom on center, maximum sheet with aft end of upper batten parallel to the boom); 12-18 means the traveler is eased about 12” down from baseline and the sheet is eased about 18” from baseline.

<table>
<thead>
<tr>
<th>Sail code (boom, sheet)</th>
<th>Twist angle, °</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boom, from centerline</td>
</tr>
<tr>
<td>0-0</td>
<td>0.1</td>
</tr>
<tr>
<td>6-0</td>
<td>1.6</td>
</tr>
<tr>
<td>12-0</td>
<td>3.4</td>
</tr>
<tr>
<td>18-0</td>
<td>4.6</td>
</tr>
<tr>
<td>24-0</td>
<td>6.1</td>
</tr>
<tr>
<td>30-0</td>
<td>8.0</td>
</tr>
<tr>
<td>0-9</td>
<td>0.1</td>
</tr>
<tr>
<td>6-9</td>
<td>1.9</td>
</tr>
<tr>
<td>12-9</td>
<td>3.3</td>
</tr>
<tr>
<td>18-9</td>
<td>4.9</td>
</tr>
<tr>
<td>24-9</td>
<td>6.1</td>
</tr>
<tr>
<td>0-18</td>
<td>-0.3</td>
</tr>
<tr>
<td>6-18</td>
<td>1.2</td>
</tr>
<tr>
<td>12-18</td>
<td>3.1</td>
</tr>
<tr>
<td>24-18</td>
<td>4.6</td>
</tr>
<tr>
<td>0-27</td>
<td>-0.5</td>
</tr>
<tr>
<td>6-27</td>
<td>1.2</td>
</tr>
<tr>
<td>12-27</td>
<td>2.4</td>
</tr>
<tr>
<td>0-36</td>
<td>0.0</td>
</tr>
<tr>
<td>6-36</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 1 – summary of sail settings

CFD modeling

Based on the analysis from AccuMeasure™, a model of each mainsail setting was developed using DesignModeler™ (ANSYS, 2009). The foot of the main was modeled as a straight line. Each of the three draft stripes (which are located ¼, ½ and ¾ of the luff from the foot) were created using NURBS curves with points from the AccuMeasure™ analysis. The twist of the lower draft stripe relative to the boom was determined by subtracting the difference in twist between the lower and upper draft stripes taken from the deck photographs from the twist of the upper draft stripe relative to the boom as shown in Table 1. The twist angle between the head and the upper draft stripe was assumed to be the same as the twist angle between the middle and upper draft stripes. The NURBS curves were used to create a surface model of the sail. An example of the sail model for sail 30-0 is shown in Figure 3:

Figure 3 – photo and surface model for sail 30-0. The backwind bubble and twist are evident in both the photo and the model.

The model for the AP jib was created in a similar manner; however, it was not possible to accurately determine the amount of twist nor the exact section shape since there was no camera at the top of the jib (the video camera at the masthead was too high to capture the jib draft stripes). Estimates of the sail shape were based on the photographs taken from the deck, as well as the lead position, shroud location, and upper spreader length and position. The total twist on the jib was estimated to be 27°.
with a sheeting angle of 8°. The camber was estimated to vary from 12% at the foot to a maximum of 16.3% at 70% of the height, and then to 15.5% at the head. Differences between the estimated shape and actual shape will change the absolute values of the predicted force coefficients, but should not significantly affect the differences between the various mainsail trims.

The complete CFD model consisted of the AP jib, the main, an elliptical prism representing the mast, and an approximated hull shape. The model was heeled to an angle of 20°, which is the optimum heel angle according to a VPP analysis from Farr Yacht Design (the designer of the boat). The boat model was placed in a three dimensional domain 100 m square by 30 m in height (by comparison the boat is approximately 11 m long and the unheeled mast height is approximately 17 m above the water). An example of the boat in the domain is shown in Figure 4:

![Figure 4](image)

Figure 4 – model of boat in domain. Positive x-axis is in the direction of motion.

The model was meshed using ANSYS Mesh™ with approximately 1.5 million tetrahedral cells. Two “sizing functions” were used to define the cell sizes. A global sizing function was used for the mast and hull which created face elements on surfaces with a minimum angle of curvature of 18° and a minimum face size of 0.02 m. These elements were expanded at a growth rate of 1.2 (adjacent element dimensions were approximately 1.2 times the original element dimensions) and a maximum element face size of 2.0 m. A local sizing function was applied to the sails with a minimum face size of 0.2 m and a growth rate of 1.2. Analyses were run with this mesh and with the mesh on the sail surfaces halved, and the resulting force coefficients were within 1% of the original values. The final surface mesh used is shown in Figure 5.

![Figure 5](image)

Figure 5 – mesh on surface of sails, mast and hull.

The wind boundary conditions consisted of the superposition of a constant boat speed of 6.3 knots along the centerline of the boat and an atmospheric boundary layer profile with a true wind velocity at the masthead of 15 knots, directed at the desired true wind angle. Simulations were performed using true wind angles of 35°, 40° (optimum according to the VPP), and 45°, which correspond to apparent wind angles of 32°, 28.5° and 24.8°, respectively. The boundary layer velocity profile is based on that used in the IMS rule (Kerwin, 1978):

\[ V(y) = 0.791 \ln(1000y + 1) \]  

(1)

where \( V \) is in m/s and \( y \) is the distance from the water surface in m. The Realizable \( k-\varepsilon \) turbulence model (ANSYS, 2009) was used with an inlet turbulent kinetic energy \( k \) of 0.577 m²/s², and an inlet dissipation rate \( \varepsilon \) given by equation (2):

\[ \varepsilon = 0.083 / (y + 0.001) \]  

(2)

These values of \( k \) and \( \varepsilon \) are consistent with the velocity profile and turbulent atmospheric boundary layers (Cook, 1995). The water surface and top of the domain were modeled as moving walls with a velocity equal to the apparent wind velocity at each elevation. The water surface was given a roughness height of 0.03 m, and the top of the domain was given a roughness height of 0.001 m. These values have been shown (Lasher and Richards, 2007) to produce consistent velocity and turbulence profiles when modeling an atmospheric boundary layer.

The simulations were performed on a Sun Sunfire v20z 2.4 GHz cluster using a single processor, which allowed several cases to be run simultaneously. Each simulation took approximately 12 cpu hours. Iterations continued until the normalized residual of each variable was less than \( 5 \times 10^{-5} \). Increasing the number of iterations by 30% generally changed the computed force coefficients by less than 1%.
RESULTS AND DISCUSSION

Effect of trim on sail shape
The photos below demonstrate how traveler position and sheet tension affect shape. Figure 6 shows the main with base sheet tension and the traveler with the boom centered, then lowered by 18” and 30”, respectively. In the first photo the main is completely full, and as the traveler is lowered a backwind bubble begins to form at the luff, then grows. In the final shot there is clearly an “s” shape to the mainsail cross-section. The photos taken from the masthead show why it was not possible to measure the section shape at the draft stripes as the backwind bubble grows.

Figure 6 – the mainsail for codes 0-0, 18-0 and 30-0, demonstrating the effect of lowering the traveler with a constant mainsheet tension.
Figure 7 shows a similar sequence with the boom always centered and the sheet eased in 9” increments. The increasing amount of twist is evident, especially in the photographs taken from the masthead. The backwind bubble is also much larger in the last photo in this sequence than in the last photo in Figure 6. In both cases any additional easing resulted in the main flogging, so it would appear that easing the sheet allows for more depowering than lowering the traveler. This is confirmed in the force data which will be presented later.

Figure 7 – the mainsail for codes 0-0, 0-18 and 0-36, demonstrating the effect of easing the sheet while maintaining a constant boom position (on centerline)
As can be seen in Table 1, lowering the traveler by 6° corresponds to an approximate 1.5° rotation of the boom to leeward. In Figure 8 the twist angle between the boom and the upper draft stripe is plotted against boom angle for each sheet tension:

![Figure 8 - twist angle between boom and upper draft stripe vs. boom angle](image)

This figure shows that the amount of twist is approximately constant for a given sheet tension, as one would expect. The variation is presumably attributable to differences in flying shape caused by changes in aerodynamic loading for various traveler positions.

In Figure 9 the average twist angle for each sheet tension is plotted against sheet tension. One would expect a large reduction in twist near maximum tension, with the rate of reduction becoming smaller as the sheet is eased due to the sail being unloaded. This appears to be the case for all but the last point in the data set, probably because the sail at this point is close to being fully unloaded.

![Figure 9 - average twist vs. sheet tension](image)

**Effect of trim on forces and moments**

The aerodynamic forces on a boat can be resolved in various directions, and two combinations are useful for the present work. Drive and side force are parallel and perpendicular, respectively, to the boat centerline, and are ultimately what is important in terms of performance. Drag and lift are parallel and perpendicular, respectively, to the apparent wind direction, and are commonly used metrics in aerodynamics to analyze and discuss performance and rig efficiency. The directions of these forces are shown in Figure 10:

![Figure 10 - drive, side, lift, and drag forces](image)

The drive and side forces for the various combinations of sail trim at a true wind angle of 40° are shown in Figure 11. All of the forces and ratios in the following analysis are plotted against heeling moment, because the objective is to determine which sail trim provides the best performance for a given heel angle (i.e., heeling moment = righting moment, Wood and Tan, 1978). For this boat heeling at 20° (the optimum heel angle according to the VPP), the righting moment is approximately 31,000 N-m, including crew weight. The points furthest to the right correspond to the boom being centered; as the traveler is eased the heeling moment and drive force decrease.

It should be noted that the predicted heeling moment is for the most part above the optimal heeling moment. This is due to the fact that the wind speed selected for the analysis was based on the maximum wind speed for carrying the AP; the sails can only be trimmed tightly if the true wind speed drops below 15 knots. One can apply the results to lower wind speeds by simply scaling the heeling moment to the wind speed of interest, so one way of interpreting the following diagrams is to consider the values at higher heeling moments to correspond to optimum settings for wind speeds lower than 15 knots.

![Figure 11(a) - drive force vs. heeling moment for 40° true wind, plotted against sheet tension](image)
Figure 11(b) – side force vs. heeling moment for 40° true wind, plotted against sheet tension

Figure 11(c) – drive force vs. heeling moment for 40° true wind, plotted against traveler position

Figure 11(d) – side force vs. heeling moment for 40° true wind, plotted against traveler position

Figure 11 shows that as the main sheet is eased, both drive and side forces increase for a given heeling moment, with the increase in side force being greater than the increase in drive force. Similarly, as the traveler is eased the drive force remains approximately constant and the side force decreases. Note that for the case with maximum sheet tension, the drive force is constant for the first two traveler positions, whereas the side force decreases as the traveler is lowered; or, for constant traveler position the decrease in side force is greater than the decrease in drive force. This means that it would be faster to drop the traveler 6° with the main sheeted hard than to leave the boom centered (or, ease the sheet 9° with the boom centered). Another way of looking at performance is to examine the drive/side force ratio, as shown in Figure 12:

Figure 12 – drive to side force ratio for 40° true wind

From this figure it is clear that the highest drive to side force ratios (a measure of rig efficiency) occur when the main is sheeted at a maximum. Also, the drive to side force ratio increases monotonically as the traveler is eased. This does not necessarily mean that it will be faster to lower the traveler – it is necessary to examine the effect of the reduced side force on the hull and keel drag, and determine whether this offsets the reduction in drive force. However, it is clear from Figure 12 that maintaining a high sheet tension and dropping the traveler produces peak rig efficiency for this type of sail configuration.

In an attempt to assess whether the increase in drive force with the sheet eased is sufficient to overcome the increase in drag on the hull due to the increased side force, the additional hull and keel drag due to side force was estimated using the model proposed by Kerwin for the original VPP, and this drag was subtracted from the drive force. A plot of this estimate is shown in Figure 13:

Figure 13(a) – difference between drive force and induced drag at 40° true wind, plotted against sheet tension
These results suggest that it is best to begin the depowering process by lowering the traveler, then easing the sheet a bit, then lowering the traveler more, then easing the sheet more. Most of the depowering should come from lowering the traveler rather than easing the sheet, but there is clearly a need to do both. It should be noted that the differences here are very small. For example, the maximum difference in corrected drive for a given heeling moment equates to a difference in performance of about 5 seconds per mile. This is not insignificant—it equates to a difference of about 2 boat lengths on a 1 mile beat—however, it is something that would be very hard to observe in a race given all the other variables, which explains why there are such divergent opinions as to what constitutes optimum performance.

The drive to side force ratio is informative from a sailing viewpoint, but it is useful to examine the lift to drag ratio from an aerodynamic viewpoint. These results are shown in Figure 14:

The drive to side force ratio graph is almost identical in appearance to those for 40°, although the drive to side force ratios are higher and the lift to drag ratios are lower for 45° than for 40°. The shape of the graphs for 35° true wind (which would be pinching) are significantly different, so the lift to drag ratio graph for this case is shown in Figure 15:

It should also be noted that the drive force from the main typically accounts for 10-12% of the total drive force, whereas the main accounts for 20-25% of the side force and 25-30% of the heeling moment. Once might infer that this means the main is ineffective; however, this would be incorrect. As the traveler is eased from boom centered to maximum lowering for a given sheet tension, the drive force on the jib typically decreases by 6-17%. Therefore it is the impact that the main has on performance of the whole sail plan that is important—not just the force on the main. This effect is well-known to sailors who understand that the main makes the boat point.

The difference in aerodynamics between lowering the traveler and easing the sheet can be understood by comparing two cases with the same heeling moment. In this comparison we will examine the vertical distributions of lift for cases 30-0 (a) and 6-27 (b). Both of these cases have heeling moments of approximately 35,800 N-m. Case (a) has maximum sheet tension with the traveler eased 30°; case (b) has the sheet eased 27° but the boom is closer to centerline (see Figure 14 for a comparison of lift-drag ratios). The spanwise lift distributions for these two cases were computed and are shown in Figure 16. Also shown is an elliptical distribution for the same lift as found in case (a).

Both cases are underloaded relative to an elliptical distribution near the base of the rig and near the head, and overloaded in the middle (i.e., the distribution looks more like a spade on a deck of cards than an ellipse). Case (a) (with the main sheeted hard) is clearly a more elliptical lift distribution than case (b). The loading on the jib in both cases is almost identical, but there is a significant difference in the loading on the main. In case (a) there is much more lift at the top of the main than in case (b), which is what one would expect. For case (b) there is an
increase in both lift and drag but a significantly lower center of effort, resulting in a similar heeling moment but increased induced drag.

Using lifting line theory (Anderson, 2001), it is possible to estimate the induced drag from the two lift distributions and compare it with the total drag (which includes form drag due to separation). The equations for downwash and induced drag were integrated numerically, and the results are summarized in Table 2:

<table>
<thead>
<tr>
<th>Sail configuration</th>
<th>(a)</th>
<th>(b)</th>
<th>Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total drag (both sails)</td>
<td>840 N</td>
<td>904 N</td>
<td>64 N</td>
</tr>
<tr>
<td>Estimate induced drag, $D_i$</td>
<td>143 N</td>
<td>201 N</td>
<td>58 N</td>
</tr>
<tr>
<td>$D_i$ for elliptic loading</td>
<td>117 N</td>
<td>121 N</td>
<td>4 N</td>
</tr>
</tbody>
</table>

Table 2 – comparison of total drag, estimated induced drag, and induced drag for an elliptically-loaded sail plan for cases (a) and (b)

In addition to the total drag and estimated induced drag, the induced drag that would have occurred if the sail plans were elliptically loaded is shown (based on the actual lift for each case). The difference in estimated induced drag calculated from lifting line theory is larger than what would be found for an elliptically loaded sail plan, and is very close to the actual difference in total drag, showing that the induced drag is responsible for all of the difference in performance.

The reason it is important to look at the induced drag as well as the total drag is that the origin of the drag provides insight into how sail trim is affecting the aerodynamics. For example, on a fractionally-rigged boat such as the Beneteau First 36.7, it is presumed that the top of the mainsail will stall earlier than the rest of the sail because there is no headsail in front to redirect the flow (this was confirmed by examining pressure plots of the mainsail). The fundamental question to be answered is whether reducing the separation at the head by increasing twist is more important than maintaining a lift distribution as close to elliptical as possible. In this case the answer is that it is more important to maintain an elliptical lift distribution.

From this analysis we can conclude that the apparent improved performance of the tight sheet configuration over the eased sheet configuration is due to the lift distribution of the tighter sheet configuration being more elliptically loaded, which is indicative of a reduction in induced drag. When the sheet is at maximum tension, the sails are underloaded at the top and overloaded at the middle relative to an elliptical distribution, so any easing of the sheet will result in less optimal lift distribution. Even though easing the sheet allows for higher forces with the same heeling moment, this is not enough to overcome the increase in induced drag.

Another factor that should be considered is the effect of sail trim on weather helm. This can be examined by looking at a graph of the yaw moment at the mast (a measure of weather helm) as shown in Figure 17:

Figure 17 – weather-helm-causing yaw moment vs. heeling moment at a true wind angle of 40º

For a given heeling moment the reduction of weather helm is greater if the sheet is eased than if the traveler is lowered. This is due to a combination of a movement of the fore-and-aft center of effort (C.E.) as well as a difference in elevation of the C.E. Since the yacht is heeled, a high C.E. increases the weather helm because the drive force is further to the side of the boat; lowering the C.E. by twisting the main therefore reduces the weather helm more than lowering the traveler.

The impact of this difference in weather helm can be assessed by estimating the change in lift force required on the rudder to balance the difference in yaw moment, and then estimating the change in induced drag due to the change in lift. This change in drag was estimated to be approximately 2 N in the present case. This is small compared to the difference in drive force shown in Figure 13, which suggests that the difference in weather helm is not a significant factor, and that performance is most likely driven by the net drive force.

There are, of course, other means of influencing sail trim, including changes to the standing rig tension, jib lead position and sheet tension, and halyard tension. These
were not studied here even though they are commonly applied in practice. Additionally, given the small differences in performance, a more definitive conclusion could be drawn if the sail forces were integrated into a VPP rather than the simplified analysis presented here.

CONCLUSIONS

A methodology for measuring the actual sail shape of a mainsail and computing the forces on the sails using CFD has been presented. This methodology has been used to investigate the effect of depowering the sail plan for the Beneteau First 36.7 by lowering the traveler and by easing the sheet. The following main conclusions have been drawn from the analysis:

1. For this boat, which is a 15/16 fractionally rigged boat with an overlapping headsail, it appears to be better to depower the rig by keeping the main sheeted hard and lowering the traveler than by keeping the traveler up and easing the sheet. More subtly, it appears to be best to use a combination of traveler easing and sheet easing, with most of the depowering coming from a lowering of the traveler.

2. The differences in performance for various sail trim settings at the same heeling moment can be attributed almost entirely to differences in induced drag, which suggests that as sailors we should try to keep the vertical loading as elliptical as possible, rather than reducing the heeling moment or weather helm by twisting the main.

3. For all cases the lift distribution is underloaded near the masthead relative to an elliptical distribution, overloaded in the middle, and underloaded near the deck. Any change which makes the lift distribution more elliptical reduces the induced drag.

It should be noted that these results only apply to this specific rig, and the results for a masthead rig or different type of fractional rig may be significantly different. Questions for future research on this topic include looking at other rig types, and the analysis of other ways of depowering the rig, including moving the jib lead aft and changing the tension of the standing rigging. The combination of this type of analysis with a VPP would allow for an examination of other questions, such as whether it is advantageous in light air to pull the boom above centerline, which is common practice on this boat.

ACKNOWLEDGMENTS

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REFERENCES


