DOWNWIND AERO MOMENTS & FORCES PHASE 2C
Final Report – January 2017

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Executive Summary

Objectives
The Downwind Aero Moments and Forces project was designed and carried out to improve the understanding of downwind aerodynamic performance related to spinnakers at deeper AWA’s.

Background
A challenge in modeling lightly loaded downwind or wide AWA sails is the tendency for the shape to oscillate, thus making it difficult to obtain a steady state convergence. Phase 2C made enhancements to the Fluid-Structure Interaction (FSI) process, including a gradual change in pressure from one coupling to the next, which, when applied, introduces sub-iterations in between the FSI couplings. These sub-iterations can help keep the solution closer to a track of structural equilibriums between couplings.

Methods
McCurdy and Rhodes 48 (M&R48) were simulated with the same S2 configuration as in Phases 1 and 2B. Sail design was created using North Sails’ “Global DesMan Design Base” and was then used by North’s design suite to create the 3D finite element analysis (FEA) models. Using North’s FEA tool “MemBrain,” these models were coupled with OpenFOAM to get a converged solution, with a sweep of sail trim adjusted and then tightly coupled each iteration to achieve a converged solution. Simulations were converged to identify the differences in sail forces and moments through a range of sail trims at one fixed boat performance. Sailing conditions were taken from the current performance targets provided.

Results
The results spreadsheets include lift and drag coefficients for the total sail plan, as well as the mast, hull, spinnaker and mainsail separately. Additionally, individual forces, moments, and center of effort locations are also listed for combined and individual components. The coordinate system is taken from a user-defined origin. Forces are reported in Newton’s, moments in Newton-meters, and dimensions in meters.

Discussion/Applications
Converged FSI solutions in steady mode were achieved without resorting to running in the far more compute intensive unsteady mode. Unsteady FSI would require a far greater number of couplings than what now were required to reach the new steady solutions in 2C. Consequently, the steady approach made it possible to run additional simulations with four spinnaker sheet variations at each of the four AWA of 85, 105, 150 and 170 degrees. By themselves these sheet variations are educational with respect to spinnaker trimming. Additionally, they can be incorporated into a VPP as an active trim parameter.
1. Introduction & Rational

After completing Phase 1, which struggled to obtain a steady state convergence at wide TWA, Phase 2C was designed to run both MemBrain (MB) and OpenFOAM in unsteady mode with a small time step to include the effect of the time gradients in the solution. At the onset of the project, this approach was thought to be necessary to obtain steady converged solutions. At each small time segment the intention was to pass new pressure to MB, run MB generating new deformed surface with velocities of deformed mesh, pass this information back to OpenFOAM and repeat for a period of time.

Sandy Wright's time was needed to modify code to help setup up the basic structure to allow an automated tighter coupling.

North Sails contributed additional software coding to activate the dynamic model in MB, and only charged for the actual simulations and the running of the new tool and not the development.

During the development process, the M&R48 would be run at a single AWA as a test case for the new methodology. When satisfied with results, additional runs would be carried out at AWA of 85, 105, 150 and 170.

The goal of Phase 2C is to have much better force and moment predictions at the deeper AWA's, (an improvement from Phase 1), and provide guidance when such a process is needed for more accurate results.

1.1. Original Methodology

Additional coding provided by North Sails to activate the dynamic model in MB was completed in the early phase of the project. Enhancements aimed at stabilizing the solution of greatly eased downwind sails, in particular the resulting unloaded luff, leech and foot edges, were put in place at the same early stage of the project.

Among these enhancements is a gradual change in pressure from one coupling to the next, which, when applied, introduces sub-iterations in between the FSI couplings. These sub-iterations can help keep the solution closer to a track of structural equilibriums between couplings. The sub-iterations can be cut short by triggering an earlier coupling when the accumulated displacements exceed a given distance away from the geometry used by the CFD in the most recent coupling.

Another enhancement, which proved useful in 2C, is the optional introduction of artificial bending stiffness along the sail edges. Even when this artificial stiffness is set low enough to have no significant effect on the deformed flying shapes, it proved to be an effective mean of preventing numerical flutter in the solution when needed.

1.2. Rationale for Changing Methodology

The enhancements made in the early stages of Phase 2C (gradual pressure changes between coupling and artificial bending stiffness along made it possible to re-run the Phase 1 M&R48 cases with greater success in terms of reaching a steady solution without the spinnaker motion swinging from side to side between couplings. As a result, it was decided that it was possible to run Phase 2C in steady mode rather than the originally intended unsteady mode.
Further upgrades completed on the OpenFOAM side by Sandy Wright at the Wolfson Unit, at first aimed at facilitating the unsteady time stepping by automating the FSI coupling, allowed for steady simulations to be run more tightly with more couplings per case than had been possible in Phase 1.

2. Results & Discussion

Converged FSI solutions in steady mode were achieved without resorting to running in the far more compute intensive unsteady mode. Unsteady FSI would require a far greater number of couplings than what now were required to reach the new steady solutions in 2C.

Consequently, the steady approach made it possible to run additional simulations with four spinnaker sheet variations at each of the four AWA of 85, 105, 150 and 170 degrees.

By themselves these sheet variations are educational with respect to spinnaker trimming. Additionally, they can be incorporated into a VPP as an active trim parameter.

For a spinnaker, current VPPs are likely to search out the maximum drive force short of any roll moment constraint at these deeper angles. However, the FSI enhancements made in Phase 2C suggest that it is feasible to run similar sheet variations for tighter angle Gennakers in a future study to provide a depowering parameter in a VPP.

2.1. Setup & Process

A generic hull surface (solid one surface deck) and mast surfaces were included in the OpenFOAM simulation, primarily to capture the effect of the hull and mast on the sails.

The origin for M&R48, was set at the bow’s projection to the waterline.

*Figure 1. M&R48 Origin*

2.2. Discussion

Figure 2 displays four trim variations for each AWA.

The four spinnaker trims on the upper row all fly at an AWA of 85. Likewise the next row down represents AWA of 105, and then comes AWA of 150, and finally AWA of 170 at the bottom. The images on the left are the tightest trim and the spinnaker sheet is eased in steps of half a meter for each set of images to the right. For each trim OpenFOAM was sequentially coupled with MemBrain until steadying at a new flying sail shape.

The spinnaker is colored by delta pressure coefficient (dCp) from the last coupling with black representing the highest pressure with white indicating back pressure.
Figure 2. Trim Variations Across AWA of 85, 105, 150, and 170
In sail aerodynamic terminology drag is the force component acting in the direction of the apparent wind, and lift is the force component perpendicular to it in the horizontal plane. Therefore, with the apparent wind abeam at 90 degrees, lift is driving the boat forward, whereas drag heels it over. As the apparent wind swings aft of abeam, the lift force gradually swings to weather, whereas the drag force gradually adds to pushing the boat forward, until fully downwind, where drag is now the sole driving force, and lift has become a rolling force to weather.

This is illustrated on Figure 3 on the next page.

The four rows of plots on this figure refer to the four rows of trims shown on Figure 1, one row for each AWA with the tightest angle abeam at the top and widest angle at the bottom. The four points marked on each curve corresponds to the gradual ease of the spinnaker sheet from left to right.

The plots on the left on each show the Cl and Cd components for each of the four trim variations shown on the corresponding row on Figure 1. Likewise the plots on the right show the Drive and Side force coefficients as well as the Roll and Yaw moment coefficients. Thus the plots on the left are the computed force – for the main sail plus the spinnaker – resolved into the apparent wind direction and perpendicular to it, whereas the plots on the right are the same computed force resolved into the boat sailing direction and perpendicular to it.

The first row with AWA 85 has the apparent wind just forward of abeam. Referring to above it can be seen that Cl is similar to Csurge, though the latter is slightly less, as drag points against the boat direction. Likewise Cd is similar to Cside.

Similarly on the second row with AWA 105 just aft of abeam Cl is also similar to Csurge, but the latter is now slightly greater, as drag here points in the boat direction. Hence the increase in Cd at AWA 105 is beneficial, which explains the increase in Csurge despite a slight reduction in Cl.

On the next row down with AWA 150 Cl has reduced to a similar magnitude as Cd without causing too much of a reduction in Csurge, as both lift and drag now drives the boat.

On the bottom row with AWA 170 close to dead downwind the contribution from Cl to driving the boat is greatly reduced, and now Cd and Csurge are similar. Here a positive Cl points to windward, which matches the negative sign of Cside.

Another way of looking at this is to say that spinnaker trimming at broad reaching is matter of generating as much lift as possible with little penalty from the resulting drag, whereas the deep downwind trim is a matter of maximizing drag. And for the latter the effect of spinnaker trim shows the least effect on drive force and more so on the tendency for the boat to roll to weather.

From Figures 2 and 3 follows that for the tighter AWA, the trim producing the most drive force exists when the luff starts to curl. For wider AWA, the optimum trim occurs prior to the luff curling.

Also plotted on the right plots on Figure 3 are Croll and Cyaw. Since Croll and Cyaw trend similar, there is no significant variation in VCE with the change in spinnaker trim.

The reduction in Cyaw as the apparent wind widens, going from positive through zero to negative, indicates the change in rudder helm.
Figure 3. Force Coefficients across the Four Trim Variations
Figure 4 below illustrates slices at a height of 10 meters that display the velocity, where dark blue and purple have very little speed and represent flow separation and or stalling – again with AWA 85 at the top increasing to AWA 170 at the bottom, and the spinnaker gradually eased from left to right.

These images support the comments made to Figure 3 in that with AWA 85 forward of abeam the goal is to maximize lift without excessive drag, whereas increasing drag gradually becomes the driver as the wind widens.

*Figure 4.10 Meter Height Slices depicting Flow Separation.*
3. Conclusion

Phase 2C achieved a better force and moment prediction at the deeper AWA's than was achieved in Phase 1 and provides guidance when this coupled process is needed for more accurate results. This same approach of sheet eased and auto coupling could be used to enhance Gennaker and Code0 simulations, such as VPP depowering.