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# New Low Drag Mast for the Star

**Spar Tech is now producing a new mast for the Star. The shape of this new mast is the result of an extensive design study using a powerful 2-D computational fluid dynamics (CFD) program. This program calculates the air flow about the mast in the presence of the jib and mainsail airfoils and includes the effects of boundary layer thickness, boundary layer transition, and flow separation.**

**The result is a new mast shape that has section drag coefficients lower than the current Star boat masts at all of the sail trim and sailing angles studied. The new mast is identified as the G-LD section (the G being the successor of the Spar Tech F-mast, and the LD for Low Drag). This new mast will have a reduced tip weight.**

## Mast Aerodynamics

Sail aerodynamics is difficult to understand for must of us. This also applies in the case of the sailboat mast. We tend to view the mast as just a device to hold our sails up, and that it produces unwanted drag because of the flow separation behind the mast. Because of this we reduce the size of the mast to reduce the drag and to reduce weight aloft. Although attempts have been made to improve mast shapes, these have been for the most part crude efforts with little knowledge of the complex airflow about the sails.

Just as the shape of the leading edge is important to the performance of an airplane wing, the shape of the mast, as the leading edge of the mainsail airfoil, is important to the overall performance of the sails.

Some have argued that the combined airfoils, jib and main, should be viewed as a single airfoil. Unlike the wing of an airplane, the complex interaction between the jib and main makes this viewpoint useless. It is this interaction between the jib and mainsail, sometimes referred to as “the slot effect”, that is not correctly understood by many sailors

A groundbreaking study was conducted back in the early '70s by the aerodynamicist, Arvel Gentry, that explained how the presence of the jib actually suppresses the tendency for high velocities to exist around the mainsail leading edge, thereby allowing the mainsail to be trimmed at a tighter angle without stalling. Likewise, the tighter trim of the main caused the jib to experience more upwash and higher velocities on the lee side of the jib, all of which gave better overall boat performance. (C.A. Marchaj, “Many problems concerning the interaction between a mainsail and a jib were clarified by A. Gentry who explained correctly, for the first time, the jib-mainsail interaction effect.”)

This complex interaction of the jib and mainsail is very important when it comes to determining the optimum shape for the mast, the leading edge of the mainsail. The mast must be designed in the presence of the jib and mainsail since it is the combined flows about both airfoils that determines the details of the pressures around the mast, and thus the mast flow separation and its effect on the overall forces of the sails. To design a mast standing alone without consideration of the jib and mainsail is a useless exercise. It gives no indication of the true performance of the mast.

The history of the Star is a fascinating story of new developments in many aspects of sailing. The same has been true on the America's Cup scene. The designer of the 12-meter *Courageous*, asked Gentry to design a new mast for use in the 1974 America's Cup defense. He also designed mast shapes used on the 12-meters *Freedom*, *Enterprise* and *Liberty*.

Last year Spar Tech asked Gentry to look at the possibility of improving the Star mast. Gentry's work took 9 months. The new G-LD Star mast is the result.

### The Mast Design Process

Some early mast designers tried to use wind tunnels in searching for better shapes. However, this was next to useless since the presence of the jib and mainsail determine the flow velocities around the mast, and thus the separation and drag characteristics of the mast. This was shown by Gentry in his research on sail aerodynamics, the interaction of two sails, and his technical paper on the mast design for *Courageous*.

The original 12-meter mast was elliptical in shape. Gentry studied a number of different mast shapes and eventually came up with a design approach that showed great promise. The idea

The Star as represented in the Boeing Aero Grid and Paneling System.

was to develop a shape which would help promote transition from laminar to turbulent flow in order to delay lee-side flow separation. This was achieved by flattening the front face of the mast and then following it with a short higher curvature region (called the knuckle). This new shape of the leading edge of the mast controlled the air flow as it accelerated around onto the lee side.

The knuckle was then followed by a sloped and much flatter region that was faired into the maximum thickness point. This sloped region gave the boundary layer time to change from the laminar to the turbulent condition; and once the boundary layer is turbulent, it is able to stay attached farther back on the mast before it separates. This is why golf balls have all the dimples.

In the early '70s the CFD program that Gentry used calculated the pressure distribution around the mast but did not include boundary layer effects. Boundary layer effects could only be accounted for by time-consuming manual iterations between the pressure CFD code and a separate boundary layer code, and even then, separation was not accurately accounted for. By looking at the pressure distribution alone you could only infer how the viscous boundary layer would react.

Actual sailing tests with new design sections attached to the outside of a conventional mast were used to understand these viscous boundary layer effects. With the large size of the 12-meter mast it was easy to conduct actual sailing tests with different mast shapes and to use a variety of flow visualization schemes (small tufts, pressure distributions, soap bubble streams, thin film gauges, special surface paint for transition detection).

In the final sailing tests the lee-side flow improvement was dramatic enough to convince the *Courageous* syndicate to order this new mast very late in the America's Cup defender trials. Using Gentry's new mast *Courageous* went on to successfully defend the Cup in '74 and again in '77. Similar designs were used on *Freedom*, *Enterprise*, and *Liberty*.

This type of testing would be very difficult to accomplish on the very small Star mast. However, Gentry thought that a modern and very sophisticated CFD code with boundary layer and separation capabilities would be useful in studying the Star mast flow problem. With consistent analysis of both the original and new mast shape candidates he might achieve a better mast design.

**The New Star Mast**

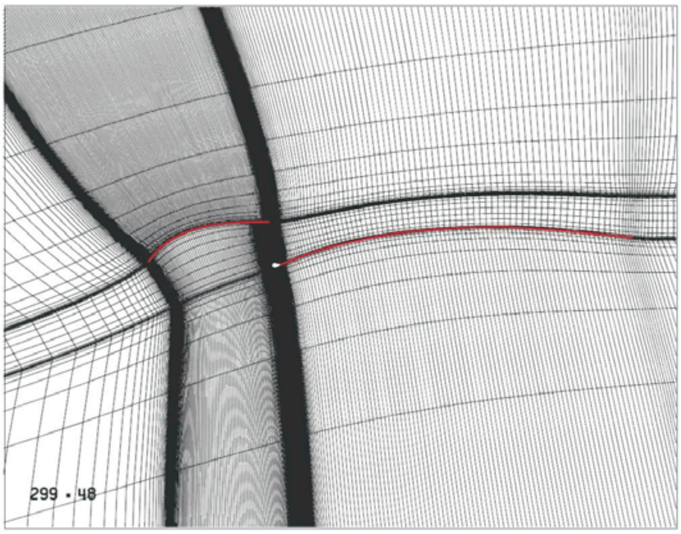
As a starting point, a set of Star sails were designed by a sail design consultant, Sandy Goodall, using his Autometrix SmSw6 sail design program. These sails were then input into a surface geometry program (Boeing's Aero Grid and Paneling System, AGPS) to give an initial three-dimensional computer representation of the Star rig and sails (see the figure on the first page).

Refinements to these sail shapes were then made within the AGPS surface geometry program using photographs of Star sails.

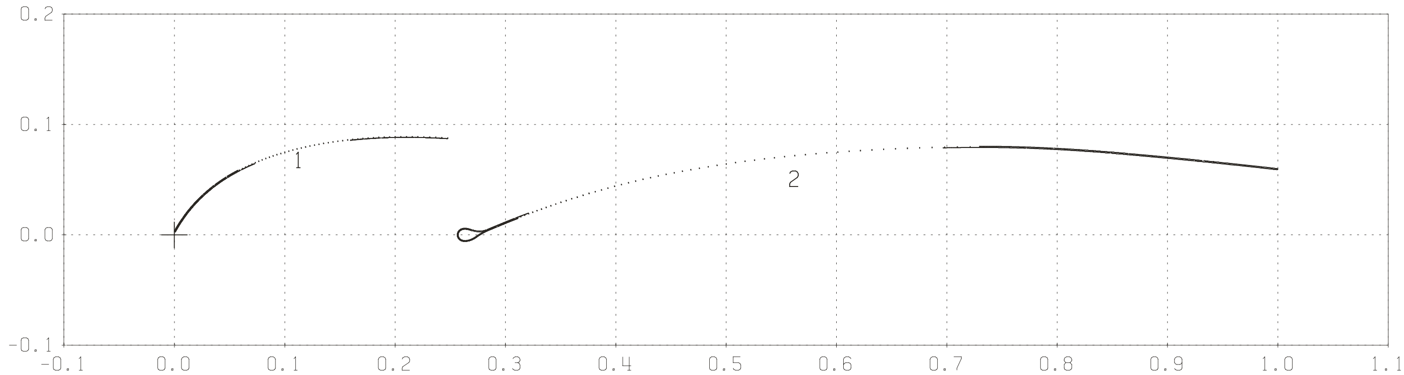
With an accurate 3-D representation of the Star and its sails in the surface geometry program, it was possible to then make 2-D cuts of the sails and mast at different heights above the deck. To assist the CFD program in starting successfully, it was necessary to create small artificial fairings between the mast and main. This would not affect the results since the final solutions would have separated flow in these regions anyway. Because the initial CFD grid was based on an inviscid panel method it was necessary to add a small thickness to both the jib and main. The AGPS program provided a file containing the jib/mast/mainsail airfoils ready for input to the CFD program. Typical input data is shown in the plot at the bottom of this page.

The CFD program was a 2-D multi-element Euler/Viscous code. The program first generates an initial grid of about 14,000 cells around the input sail shapes. A portion of this starting grid is shown in the plot below. The grid density is so high that the mast and sails are almost hidden within the mass of grid lines.

It then solves the Euler flow equations in an iterative process. During this process the boundary layer properties (laminar/turbulent, separation, thickness) are calculated and used to adjust the grid cells to obtain a final converged solution for the flow field around the sail and mast combinations. The most




A portion of the initial starting inviscid grid about the jib/mast/mainsail combination.




Airfoil data as input to the CFD program.

important output was the section lift and drag coefficients of the jib/mast/mainsail airfoil combination.

Program output data also included details such as laminar-to-turbulent transition point, laminar separation bubbles on the mast itself, and final flow separation regions behind the mast.

The angle of attack of the airfoil combination was varied on each run to ensure that the flow over the jib and main was realistic and represented realistic sailing conditions. Runs were also made using sail cuts at different heights above the deck

In a series of computer analysis runs the shape of the new mast was varied in attempts to achieve a lower drag. In each case the computer analysis runs were made with both the new mast candidate and the original Spar Tech F-mast.

The original F-mast shape is basically made up of portions of three circles, with the front face being quite round. It "looks" nice and smooth, and looks like a low drag shape. However, in the CFD code, the flow tended to completely separate well forward on the mast.

The same general ideas used on the 12-meter mast design were tried on the Star mast. The early computer runs were very promising and a number of computer runs were made to verify the results.

The bend of the Star mast is adjusted over a wide range to optimize the mainsail shape for varying wind and sea conditions. To account for this, CFD computer runs were also made with varying jib sheeting angles and using different mainsail flatness parameters. Runs were also made at different mast heights and at different wind speeds (Reynolds number).

A number of possible changes in the details of the mast shape were then investigated to find the design parameter limits that still produced improved section lift and drag characteristics when compared with the standard F-mast under the same flow conditions.

The result of these studies was a new mast section shape that had lower drag then the current Star mast under all sail trim and sailing angles studied. Under many of the sailing conditions it was found that the new G-LD mast had a small separation bubble on the sloping transition region that caused the flow to change from the laminar to turbulent condition before the widest point of the mast was reached.

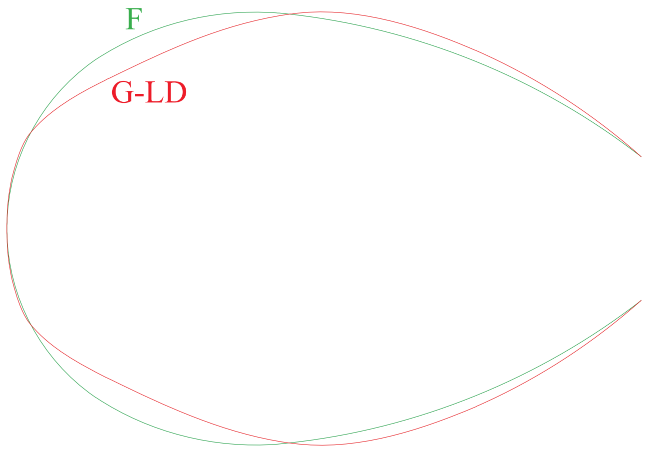
This showed that it was possible to cause the boundary layer to change from laminar to turbulent flow in an attached separation bubble without the use of trip devices; and when the flow is turbulent, it remains attached longer before separating near the mast maximum thickness point..

This was achieved without having any hollows or trip devices on the mast shape in order to stay within the International Star Class rules. Even for the flow conditions where the transition bubble was not completely formed, the jib/mainsail combination with the new mast had lower drag than with the standard F-mast. Improvements in the flow around the mast also improved the flow over the mainsail, which in turn helped the flow over the jib. It makes no sense to look at the drag characteristics of the mast alone.

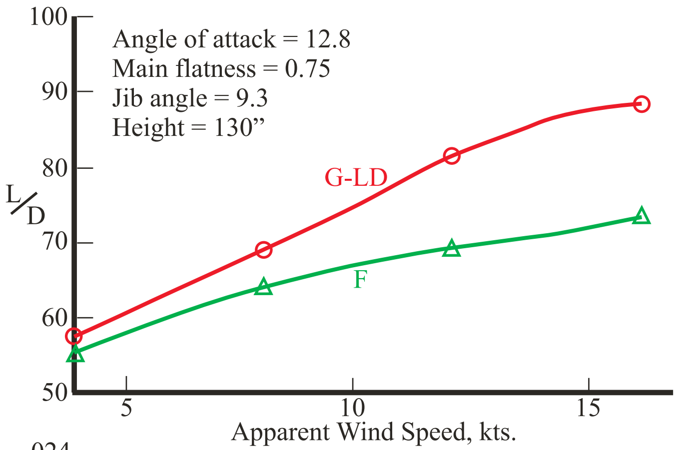
In reviewing the output data from the CFD program, special attention was paid to the section Lift over Drag (L/D) produced by the configuration. In all the cases run, the sail configuration with the G-LD mast had a higher section L/D than with the F-mast. This came from a slight increase in lift coefficient ($C_L$), and a significant reduction in section drag coefficient ($C_D$) of the whole configuration.

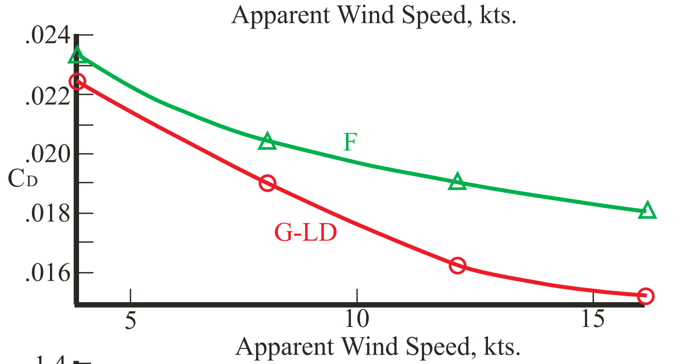
The improvement was the smallest at the lower wind speeds and increased dramatically at the higher wind speeds.

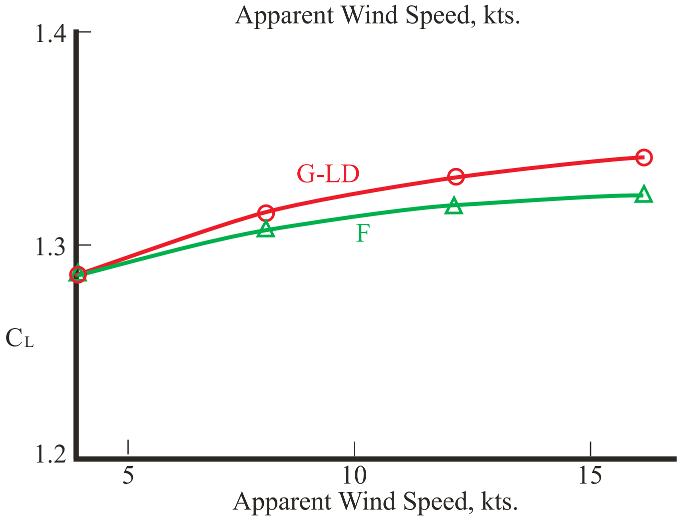
The section lift and drag characteristics calculated at different Reynolds Number (wind speed) for the G-LD mast are shown in the plots below and compared with the F-mast under the same flow conditions.



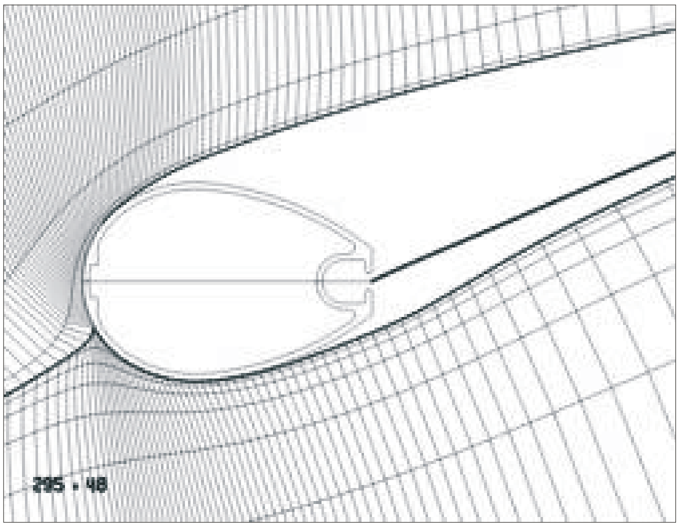

Comparison of G-LD and F sections.



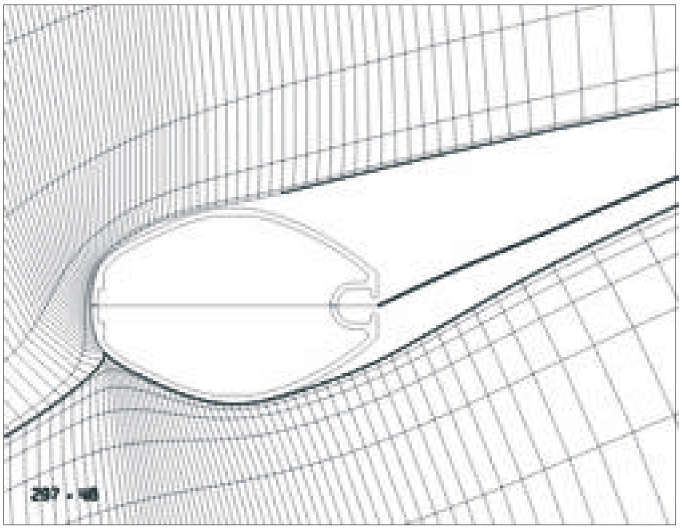



A good understanding of where the G-LD mast improvements come from can be seen by comparing the final grid plots around the mast sections. Sample plots for the F and G-LD masts at the same flow conditions are shown below.




Final solution grid for the F-mast. Note the forward position of the flow separation as compared to the G-LD mast below.




Final solution grid around the G-LD mast. The flow conditions and sail shapes were the same as for the F-mast plot above. The separation on the lee-side of the mast is significantly reduced.

How much of this drag improvement will be seen on the water? That is always a tough question. All of components contribute to the final total lift and drag of the boat. Most of these, such as rig drag, are very hard to assess. The analysis conducted in this design effort used only 2-D tools. For an aerodynamicist, this is always the starting point in a wing design effort. You design a good 2-D airfoil first, then look at the 3-D effects.

The lift and drag values shown used in this study are identified as the "section" lift and drag since they are simply the characteristics of the two-dimensional characteristics of the airfoil sections (combined jib/mast/mainsail coefficients in this case).

The total drag of a lifting configuration includes the airfoil section drag, plus the drag due to 3-D effects. The 3-D effects come from the fact that the sails (or wing) have a finite length. The ratio of the wing span to the average chord length is called the aspect ratio. A very long wing, like on a glider, has a lower drag due to 3-D effects than a conventional light plane. This 3-D drag is called drag-due-to-lift, or "induced drag." On sailboats we would really like to make the sails very tall, but unfortunately have to worry about the higher heeling force caused by moving the sail center of effort upward.

Under useful lifting conditions the induced drag contribution is larger than the 2-D section drag such as studied in this mast design effort. In other words, the lift and drag improvements shown in this study are only a part of the total lift and drag picture of the sails.

Why did this study not use a more sophisticated CFD program that would include these 3-D effects? There are a number of problems in doing this, but foremost is that such codes require the use of a very powerful workstation or even a supercomputer since viscous effects are so important in the mast design process. Also, such programs available in the aircraft industry would require modifications to handle the wind gradient up the sails. The computers used in this study were conventional PCs running both Windows XP and Linux.

Also, on a sailboat the induced drag component changes every time we change the sail sheeting conditions.

As with many aspects of sailing, improved performance is the result of a number of factors, and even small increments add up to winning on the water.

After the mast shape studies were completed the effort was switched to the interior design of the mast. A program was written to allow quick iterations on the internal shape parameters and to provide input to a new moment of inertia computer program. The moment of inertia program was written using Compaq Visual Fortran. This program was derived from a triangular unstructured grid generation program obtained from NASA. AGPS generated the input data for the moment of inertia program and allow iterations on the internal shape components.

The goal for the interior design of the mast was to achieve the desired mast stiffness and weight.


Who Is Arvel Gentry?
For more information on Arvel's technical background and contributions to sailing technology go to www.arvelgentry.com.