A Comparison of Experimental and Theoretical Sail Forces

By

Andreas Kirschmer Klein

B.S. Naval Architecture and Marine Engineering
Massachusetts Institute of Technology (1987)

Submitted to the department of Ocean Engineering in partial fulfillment of the requirements for the degree of

Master of Science in Naval Architecture and Marine Engineering

at the
Massachusetts Institute of Technology February, 1990
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Signature of Author

[Signature]

Department of Ocean Engineering
January 30, 1990

Certified by

Jerome H. Milgram
Jerome H. Milgram
Thesis Supervisor

Accepted by

A. Douglas Carmichael
Chairman, Department Committee
A Comparison of Experimental and Theoretical Sail Forces

Andreas Klein
Department of Ocean Engineering

Abstract

A comparison between experimentally measured sail forces and inviscid theory for identical sail shapes is presented. A video image processing system was developed to simultaneously measure and record sail shapes using a personal computer. The sail forces were measured on the MIT Rig Force Test Boat sailing dynamometer for close hauled conditions. A 3-D vortex lattice computer model was used to predict the sail forces generated by the recorded sail shapes.

Results revealed the importance of viscous effects on the performance of sails. The superposition of viscous drag on the inviscid solution improved agreement between experiment and theory in all cases. The jib only and main and jib combined cases evidenced good agreement overall. Estimates of viscous effects, however, were unable to account for a large discrepancy in the forward force component for the main only condition.

Thesis Supervisor: Jerome H. Milgram
Title: Professor of Naval Architecture
Acknowledgements

I would like to sincerely thank my advisor, Prof. Milgram, for his support throughout this project.

I would also like to thank David Greeley of Atlantic Applied Research for so gratiously providing me with his program.

I thank my lab mates, Buddy Duncan, Jim Herman, and Hasan Olmez, for their assistance and for making these past two years so enjoyable.

Finally, I thank my family, and especially Jen, for their unyielding encouragement, support, and motivation, without which this project would not have been possible.

Some calculations in this paper were performed on the M.I.T. Supercomputer Facility CRAY-2.
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1. Introduction

In recent years, increasing attention has been paid to the analytical design of yacht sails to optimize their performance. To this end, computer codes have been developed to solve both the design problem, calculating the shape needed to yield a given loading and the analysis problem, calculating the loading on a given shape. If the extent of advertising is any measure, these efforts have met with considerable success. However, the true accuracy with which the results of these models can be extended from theory to the real world has been difficult if not impossible to gauge.

The performance of a sailing yacht under any given conditions is a complex function of innumerable variables from the boat to the sails to the crew. Attempts to measure the performance of sails by extension from the performance of the boat as a whole is therefore prone to error and of limited accuracy. The vessel employed in this study is unique in that it has been designed to directly measure the forces on the boat's rig. This study presents a comparison between the forces acting on a set of sails as measured in real sailing conditions and the prediction of a computer-based sail aerodynamics mathematical model.

This study has been conducted for two reasons: to determine what modifications need to be made to model
performance predictions to bring them into agreement with real world experience, and to provide a data base with which further developments in such programs can be measured. This information is needed for future optimizations of sail performance.

The thesis is naturally divided into two parts: the experimental measurement of sail shapes and forces, and the subsequent comparison with the theoretical model. In order to be able to make any valid comparisons not only did the forces need to be accurately measured, but also the conditions which resulted in these forces had to be measured. These critical conditions included wind speed, direction, and profile, and the shape of the sails on which the wind acted. All experiments were conducted on the MIT sail force test boat in October of 1989. The recording of the sail shapes was performed using a video image processing system developed for this study.

The sail shapes recorded with the image system served as the input to a vortex lattice computer model running on the MIT Cray II supercomputer. The computer model was obtained from Atlantic Applied Research Corporation and is described by Greeley [3]. This model was used to calculate the forces generated by the given sail shape and the results were compared to the forces measured on the test boat.
2. Sail Shapes Through Video Image Processing

The first stage of this project centered on describing the shape of the sail during the experiments. A sailboat sail going up wind acts for all intents and purposes as a lifting wing. As such, the geometric description for wings applies to sails: the span is defined as the height extending normally along the mast for the mainsail, and the chord as perpendicular to the span, extending parallel to the boom or foot. A chord line at any height is defined as extending horizontally from the leading edge at that height to the trailing edge (see Figure 1). The camber of the sail as a function of the chord is then measured as the perpendicular distance from this line to the surface of the sail itself. The twist of the sail at any height is defined as the angle between the chord line and the centerline of the boat. The local angle of attack can then be determined

Figure 1: Mainsail geometry.
as the difference between the local twist and apparent wind angles.

The shape of a sail under load depends on many factors. The sail maker has already determined much of its shape through the size, shape, and orientation of the panels sewn together to form the sail. When sailing, the loading on the sail due to the wind also influences the shape. Since the sails are made from fabric, they are flexible and deform in response to loading. The shape can be controlled to a limited extent by the sailor adjusting tension in the sail with a combination of outhaul, downhaul, and sheets.

Obviously, defining the shape of a sail on a moving boat is a very complicated affair. Direct measurement of the sail is next to impossible even under the best of conditions. Since there are no convenient references from which to measure, one can hardly be expected to hang from the rigging with a tape measure. Indirect methods must be used make the measurements necessary to define the sail's shape.

The first step is to simplify the problem with a few judicious assumptions about the shape of the sail to be measured. Given that a well trimmed sail is smooth, the shape of the sail as a whole can be described by interpolation between a small number of points. The minimum number that can be used depends on the complexity of the anticipated sail shape. Figure 2 shows a typical smoothly
loaded cross section and a slightly backwinded section (as can be expected on the main near the region of jib overlap). The first can be approximated with a second order function while the second needs at least a fourth order function. Therefore, in order to cover the full range of expected sail shapes, we had best assume fourth order shape in both directions for the sail as a whole. Since five equations are needed to solve for the five unknowns, the locations of at least five points on the curve must be known in either vertical or horizontal directions. The whole sail can be defined by a grid with a minimum of 25 points.

![Second Order and Fourth Order Sail Crosssections](image)

Figure 2: Predicted Sail Crosssections

The most commonly used method to determine sail shape involves taking still photographs either from the deck or from another boat (see Figure 3). The dimensions of the sail are scaled from measurements made directly on the photograph. This method is time consuming and prone to scaling error. The simple fact that the film needs to be developed means that there is a delay before the results are
available. It was decided that this method would not be suited to this thesis.

Over the last couple of years, a new approach has been developed independently by several groups. This method combines video cameras and personal computers in an image processing system which has the potential to determine the shapes of sails in real time. Video cameras are mounted on the mast head or in the deck and provide a continuous source of images to the computer. These images are then scanned to identify chordwise stripes on the sail and their positions

Figure 3: Photograph used for measuring the shape of a sail. Photo courtesy Nauticus Marina.
within the image are accurately translated to their true positions in space. This information can then be used to measure the relevant descriptive quantities: span- and chordwise distribution of twist and camber.

Unfortunately, only one such system is commercially available at this time. This system was judged to be too inaccurate and cumbersome to justify its price -- nearly $60,000. Instead, we undertook the development of a video image processing system of our own for use on the MIT sail force test boat. The system was built from off the shelf components for less than $3000. The issues encountered in the design of this system are presented in the remainder of this chapter.

The video system can be broken down into three main components: the computer, the camera, and the interface between them, the frame grabber. There are several design issues which bear on the selection of each of these components: speed, resolution, and cost. The selection of each component depends on the others since they must be properly matched to maximize their potential.

The first concern to be addressed in the selection of the video system components is the placement of the camera(s) as this will determine the size and orientation of the image to be viewed. Two obvious choices present themselves in this application: on the deck pointing upward (Figure 4) and on the mast head pointing downward (Figure
Each has advantages and disadvantages which were weighed against each other. The deck mounted system is easy to service and align. It remains fixed in the boat coordinate frame and therefore only needs to be calibrated once. However, this system is very close to the boom and requires a rather wide angle lens to view it. The issue is worsened by the fact that the shortest stripe (a few feet below the head) is foreshortened by the distance and dwarfed.
by the dimension of the image at that distance. This imposes a severe limitation on the resolution at that stripe.

The mast head mounted system, however does not suffer this problem. The foreshortening of the longer stripes in this case with distance means that all of the stripes appear to be roughly the same length in the image. This serves as an optimal use of the image size (best possible pixel to length ratio) over all the stripes. As a disadvantage, the mast head camera is difficult to access. More importantly the camera also changes orientation relative to boat coordinate frame as the mast bends and twists under load. This is especially true on the fractionally rigged test boat where the top quarter of the mast is unstayed. The camera calibration is based on points fixed relative to the camera, so as the camera moves it must be continuously calibrated to maintain accuracy.

The mast head mounting position was used for this project. This decision was based on its superior resolution and the fact that, at the time, it was the only configuration known to have been used by others. In order to reduce the difficulties associated with the changing camera orientation, a standard calibration scheme had to be modified to increase its flexibility and speed.

The images of the sails were made with a standard black and white analog video camera used extensively in the surveillance and robotics industries (Figure 6). A video
camera consists of a lens which focuses an image onto a light sensitive array. The array contains discrete sensors, pixels, which produce signals proportional to the intensity of light striking them. The sensors are read in sequence at a specific frequency to generate the video signal. The number of sensors in the array and the focal length of the lens determine the ultimate resolution of the image system as a whole.

![Image of video cameras](image)

**Figure 6:** Video cameras used in the imaging system. Note the weatherproof case needed to protect the cameras from the elements.

The industry standard high resolution array has 512 pixels horizontally and 492 pixels vertically. Thus, the image system can resolve objects to an accuracy of $1/511$th of the image size in the horizontal dimension and $1/491$th of the image size in the vertical dimension. The size of the image striking the array and therefore the overall perceived size of the image is determined by the choice of lens focal length. The best system resolution for a given array is
attained by selecting a lens which projects the object of interest to fill the image without exceeding its boundaries -- the idea being to maximize the number of pixels per target object length.

The critical link that makes the whole system possible is the frame grabber which connects the camera and computer. This piece of hardware is typically mounted on a standard expansion card and connects directly to the host computer's bus (Figure 7). The frame grabber first takes an analog video signal (in this case, black and white) from the camera and converts it to a digital signal at a standard rate of 30 frames per second. The digitized signal passes through a 'look-up table' where each 8 bit pixel value is mapped either to a specific color or grey scale value. The result

![Figure 7: MV1 framegrabber functional block diagram. Courtesy MetraByte.](image-url)
can then be displayed on a monitor or loaded into memory (frame grabbing) under the direction of the user. Once in memory, the contents of the image can be accessed and manipulated by the host computer. The frame grabber chosen for this system was the MetraByte MV1.

The image processing task of the computer can be divided into three functions: the calibration of the camera based on a best fit mapping to known positions, the location of the sail stripes and their mapping from image to boat coordinates, and the characterization of the sail shapes based on the locations of the sail stripes in space. For the number of points being considered here (the minimum 25 grid points), the most time intensive function is the stripe finding. In order to make the system run as close to real time as possible extensive efforts were made to streamline this function: searches were performed only within windows and filtering was kept to a minimum.

Figure 8 outlines the stripe finding strategy. First, the beginning of a stripe is located within a fixed search window. This window was located at the intersection of the stripe and the mast since it is reasonable to expect that this point will remain relatively fixed in space. The window was sized sufficiently to account for some movement of the intersection due to mast bend and change in camera orientation. Once this point had been determined, the stripe was followed from the mast out to the trailing edge.
Figure 8: Stripe finding scheme block diagram.

The stripes were followed, from column to column, by finding the rowwise position of the darkest pixel or average rowwise position of darkest pixels in a vertical raster search window of ten to twenty pixels. From this point, the window was stepped forward one column, centered on the row predicted to be the location of the next darkest row based on linear extrapolation from the last two or three positions. In the event a darkest pixel could not be found in the window, a linear step would be assumed and the raster window enlarged in case the followed path was diverging from the stripe. The searching was performed in a windowed fashion to reduce computation time by keeping the number of pixels processed to a minimum.

The stability of this scheme (i.e. its tendency to follow the stripe rather than shadows, seams, or creases)
was improved by imposing limits on the slope and on the change in slope used to advance the search window. Since the stripe can be assumed to be smooth, abrupt changes in slope can be ignored effectively filtering the results. Additional conditions such as minimum stripe contrast and edge detection were imposed, however, they proved ineffective and at times destabilizing. In the end, stability proved to be the source of the greatest frustration. A mouse driven routine was then designed into the image processing program to allow manual identification of stripe points for this thesis. Work on the automatic detection of stripes is planned for the future. All of the shape data presented in this report was obtained using the mouse driven routines.

The visibility of the stripes also proved to be an important issue. On the first attempt, the stripes were simply bands of black tape stuck to the sail, but since they were being viewed at very acute angles, their profiles as seen in the image were too small. Glare, even in the best conditions, tended to obscure large parts of the stripes. Half round pieces of foam tubing were later placed under the tape. This had the desired effect of increasing the profile of the stripes making them visible in nearly all situations.

Before the stripe locations could be translated into real space, a function mapping image to boat coordinates had
to be determined of the form:

\[ x, y = f(u, v) \]  \hspace{1cm} (1)

where: \((x, y)\) are boat coordinates and
\((u, v)\) are the corresponding image coordinates.

Figure 9 shows a schematic of the camera calibration geometry. Standard world to image polynomial mapping functions of the form:

\[ u = ax + by + c \]  \hspace{1cm} (2)

are valid only as long as the orientation of the camera remains fixed in the reference frame [16]. Since the video image is limited to two dimensions, there is no way to resolve distance away from the camera. A function of the form (2) only applies to a single fixed distance between

![Diagram](image-url)
object and camera [15], [17]. For this reason, the approach was modified by defining the locations of all points as offsets from a single point vertically below the camera. The offsets calculated were further considered to be projections of the true offsets onto a sphere centered at the camera with a radius, $R$, equal to the distance to the object in question. Thus, the offsets can be considered angular offsets rather than linear offsets. The primary advantage to this approach is that a single mapping function holds for all points in parallel planes; the offsets simply scale as linear functions of distance from the camera (similar triangles). The offsets are taken from a point directly below the camera since this one point has the same coordinates in each plane parallel to the deck for every height in the boat coordinate frame.

With the above mentioned modifications, equation (2) can be expressed as:

$$
\begin{align*}
su &= a_{11} \, dx + a_{12} \, dy + a_{13} \\
sv &= a_{21} \, dx + a_{22} \, dy + a_{23} \\
s &= a_{31} \, dx + a_{32} \, dy + a_{33}
\end{align*}
$$

(3)

with: $s$ = some arbitrary scaling factor, and $dx, dy$ = angular offsets such that:

$$
\begin{align*}
dx &= \tan^{-1}\left(\frac{X - X_0}{Z}\right) \\
dy &= \tan^{-1}\left(\frac{Y - Y_0}{Z}\right)
\end{align*}
$$

(4)

where $(X,Y)$ are the boat coordinates of some point and $(X_0,Y_0)$ are the coordinates of the point directly below the camera from which the offsets are measured. This can be
written in matrix form as:

\[
\begin{bmatrix}
    su \\
    sv \\
    s
\end{bmatrix} =
\begin{bmatrix}
    a_{11} & a_{12} & a_{13} \\
    a_{21} & a_{22} & a_{23} \\
    a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
    x \\
    y \\
    1
\end{bmatrix}
\]  \hspace{1cm} (5)

Eliminating the scaling factor by solving for \(u\) and \(v\) yields:

\[
\begin{align*}
    u &= a_{11} \text{d}x + a_{12} \text{d}y + a_{13} - a_{31} \text{d}x \, u - a_{32} \text{d}y \, u \\
    v &= a_{21} \text{d}x + a_{22} \text{d}y + a_{23} - a_{31} \text{d}x \, v - a_{32} \text{d}y \, v
\end{align*}
\]  \hspace{1cm} (6)

with a total of eight unknown coefficients. The calibration of the camera is the process of defining the boat to image mapping function (3) for the camera by solving for these eight coefficients. The minimum of eight equations needed to solve for the coefficients can be written in matrix form:

\[
\begin{bmatrix}
    \text{d}x_1 \, \text{d}y_1 & 1 & 0 & 0 & 0 & -\text{d}x_1 \, u_1 & -\text{d}y_1 \, u_1 \\
    0 & 0 & \text{d}x_1 \, \text{d}y_1 & 1 & -\text{d}x_1 \, v_1 & -\text{d}y_1 \, v_1 \\
    \vdots & & & & \vdots & & \\
    a_{11} & a_{12} & a_{13} & a_{21} & a_{22} & a_{23} & a_{31} & a_{32}
\end{bmatrix}
\begin{bmatrix}
    u_1 \\
    v_1 \\
    \vdots \\
    u_n \\
    v_n
\end{bmatrix}
\]  \hspace{1cm} (7)

Any number of matrix solution techniques can be used to solve for the \(a_{ij}\) coefficients matrix. The \((\text{d}x, \text{d}y)_i\) terms are the angular offsets calculated from the known locations of at least four points (calibration points) in the boat coordinate frame. The \((u,v)_i\) terms in these equations are row and column coordinates, respectively, of these same four calibration points as they appear in the image. In this
project, the calibration points were defined by four crosses of black tape spread out from each other on the deck to maximize the resolution in the horizontal direction. These marks were efficiently located within the image by searching within specified windows. The calibration accuracy can be improved somewhat by increasing the number of calibration points and solving a least squares fit to the coefficients of matrix (7). In the interest of speed however, the minimum number of points, four, was used. These were determined in the laboratory to be sufficient for accuracies better than one pixel width.

Once the coefficients $A_{ij}$ have been calculated, they can be applied to map all of the stripes provided:

1. the heights of the stripes are known,
2. the stripes remain in planes parallel to the plane of the calibration marks.

The conversion from image to world coordinates can be performed in matrix form following (5) or explicitly:

\[
x = R \tan dy + x_0 = R \tan \frac{eu - dv + a_{13} - a_{23}d}{ea - bd} + x_0
\]

\[
y = R \tan dy + y_0 = R \tan \frac{av - bu + a_{13} - a_{23}a}{ea - bd} + y_0
\]

where:

\[
a = a_{11} - a_{31}u \\
b = a_{21} - 31v
\]

\[
d = a_{12} - a_{32}u \\
e = a_{22} - a_{32}v
\]

Recall (from Figure 9) that $R$ is the vertical distance from
the camera to the point \((X_0, Y_0)\) in the plane of the stripe in question.

The remaining processing task involves defining the shape of the sail in terms of the twist and distribution of camber given the boat coordinates of the stripes. This was accomplished in three steps. First, the coordinates of the intersection of the mast and stripe, the leading edge location, were subtracted from all coordinates of the stripe, effectively shifting the leading edge to the origin. The chord line was then defined as extending from the leading edge to the trailing edge. Second, the entire stripe was rotated to bring the chord line coincident with the horizontal axis using the following formulation:

\[
\begin{align*}
    x' &= \left[ (x - x_0) \cos \varphi + (y - y_0) \sin \varphi \right] + x_0 \\
    y' &= \left[ -(x - x_0) \sin \varphi + (y - y_0) \cos \varphi \right] + y_0
\end{align*}
\]

(11)

where \(\varphi\) is defined

\[
\varphi = \tan^{-1} \frac{Y_n - Y_0}{X_n - X_0} = \tan^{-1} \frac{Y_n}{X_n}
\]

(12)

The twist angle of that section is then \(\phi\) or \(180 - \phi\) depending on the orientation of the stripe relative to the positive \(x\)-axis. Finally, the camber values as functions of the chord were read off as vertical offsets above the horizontal axis. The values thus computed uniquely defined the shape in a standardized format that simplified comparison with similar sails.
3. Experimental Measurement of Sail Forces

The aerodynamic force on a sail can be expressed in terms of components perpendicular and parallel to the wind direction: lift and drag. The magnitude and direction of the resultant force defines the powering force on a sailboat. The component of the rig force in the forward direction propels the boat along its course, while the perpendicular component must be countered by the keel and rudder. Figure 10 depicts the forces acting on a sailing rig. These forces are balanced by the lift and drag forces generated by the hull in the water. Figure 11 shows part of the force balance which determines the equilibrium condition of the boat. There are three perpendicular force components and three perpendicular moments which act on the sailing craft. The forces of lift and drag can be resolved in the forward

![Diagram of sailboat forces](image)

*Figure 10: Forces acting on a sail.*
and lateral directions by:

\[ F_x = L \sin B - D \cos B \]  \hspace{1cm} (13)  

\[ F_y = L \cos B + D \sin B \]

where \( L \) is the lift force and \( D \) is the drag force. \( B \) is the apparent angle of the wind relative to the center line of the boat. \( F_x \) and \( F_y \) are known as the forward and side forces, respectively.

The experiments described in this report were conducted on the MIT sail force test boat which is uniquely designed to accurately measure the forces and moments generated by the wind on its sails (Figure 12) [5]. Every component of the boat’s rigging is attached directly to a frame inside the hull which does not touch any part of the shell of the boat. This frame is connected to the hull only through six tension/compression load cells. After the fraction of the
Figure 12: MIT Rig Force Test Boat, profile and plan views of frame and interior.

rig load attributable to the frame’s weight has been subtracted out, the loads measured by the six cells are used to resolve each of the three forces and three moments.

The load cells translate tensile or compressive stress into an analog signal which is converted to a digital signal in the onboard personal computer. Readings are averaged over time and converted to relevant units based on a best fit calibration. The time averages of the forces are recorded at periodic intervals along with boatspeed, heel angle, apparent wind speed and apparent wind direction.
Fourteen separate tests were conducted for this report on October 14, 1989 with variations on three rig configurations: main only, 100% jib only, and main and 100% jib together. Table 1 shows the trim conditions for each of runs. The tests were run upwind, close hauled, approximately 1/2 mile from the entrance to Marblehead, Mass. harbor. The twist and draft of each sail was adjusted from run to run in order to judge the effects of each. Each of the runs averaged ten minutes and covered one half nautical mile.

The camera images were recorded on video tape during each test with cameras mounted at the mast head (main sail view) and just below the headstay (jib view). During runs rigged with both sails, the signal to the recorder was manually switched back and forth at ~45 second intervals to allow views of each sail. The video tape was processed later in the laboratory to determine the sail shapes during each run.

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<td>med</td>
<td>low</td>
</tr>
<tr>
<td>2</td>
<td>main</td>
<td>med</td>
<td>med</td>
</tr>
<tr>
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<td>main</td>
<td>max</td>
<td>low</td>
</tr>
<tr>
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<td>max</td>
<td>med</td>
</tr>
<tr>
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<td>main</td>
<td>min</td>
<td>low</td>
</tr>
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<td>min</td>
<td>med</td>
</tr>
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<td>main + 100% jib</td>
<td>max</td>
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Table 1: Summary of sail trim settings for tests run on October 14, 1989
4. Theoretical Prediction of Sail Forces

As a simple approximation, the circulation about a sail can be considered to be concentrated on a single spanwise directed bound vortex line in a uniform flow field such that $\Gamma = \Gamma(y)$. Kelvin's theorem (no net circulation about a closed contour in a potential flow) is satisfied by a sheet of trailing vorticity (free vorticity) where:

$$\zeta_f(y) = -\frac{d\Gamma}{dy}$$  \hspace{1cm} (14)

This problem can be analysed in discrete form by breaking the lifting line up into smaller segments with bound circulation, $\Gamma(n)$, constant over the length of the the segment. The free vorticity is concentrated in two semi-infinite vortex lines, one at each end. This method of breaking the lifting line into smaller, discrete, horseshoe shaped segments is commonly termed the discrete lifting line method (Figure 13).

Figure 13: Discretization of lifting line into horseshoe vortices.
The total force generated by the lifting line results from the fluid flow past each incremental unit of bound vorticity. Locally, the flow over each segment on the lifting line can be broken down into two perpendicularly oriented components: the freestream velocity, $U$, and the downwash, $w^*$. The latter is the flow induced at the lifting line by the free vorticity in the wake. These two velocity components give rise to two perpendicularly oriented forces: the lift which acts normal to the freestream direction, and the induced drag which acts normal to the downwash direction (in the freestream direction).

From Kerwin [7], if the lifting line is divided into $M$ segments, the downwash induced by the free vorticity on the $n$th segment can be calculated by:

$$
w^*(n) = \frac{sU}{2\pi} \left[ \frac{\Gamma(1)}{y_v(1) - y_c(n)} - \sum_{m=1}^{M+1} \frac{\Gamma(m+1) - \Gamma(m)}{y_v(m+1) - y_c(n)} \right] - \frac{\Gamma(M)}{y_v(M+1) - y_c(n)}$$

(15)

where $y_v(n)$ are the $y$ coordinates of the segment end points and therefore the free vortex lines. $y_c(n)$ are the discrete 'control' points in each segment at which the function is evaluated (one per segment). One look at the equation for the induced velocity shows that the choice of control point cannot be arbitrary since $w^*$ is singular for all $y_c(n)$ coinciding with $y_v(n)$. It has been found empirically that a choice of $y_c(n)$ in the center of each segment in the case of equally sized discretizations gives accurate results.
A flow, \( v \), passed a vortex results in a force normal to the inflow direction given by the familiar:

\[
F = \rho v \Gamma
\]  

(16)

In discrete form, for the lifting line described above, the lift and drag can be expressed:

\[
L = \rho U \sum_{n=1}^{M} \Gamma(n) \left[ y_{V}(n+1) - y_{V}(n) \right]
\]  

(17)

and

\[
D = \rho \sum_{n=1}^{M} v^*(n) \Gamma(n) \left[ y_{V}(n+1) - y_{V}(n) \right]
\]  

(18)

The discrete lifting line method can be extended into three dimensions to model the surface of a sail. The circulation around a sail can be considered concentrated in a sheet of spanwise directed discrete vortex lines (i.e. distributed along the chord). Further, each of these vortex lines can be discretized along its length to form a mesh of panels with coincident trailing vortex lines (Figure 14). This is known as the vortex lattice method.

Extending the lifting line problem into three dimensions introduces complications. The strengths of the distributed bound vortices must now be chosen such that the physical constraints in the problem are not violated. The following boundary conditions must be satisfied:

1. zero net normal velocity on the surface of the sail, and
2. zero flow around the trailing edge (Kutta condition).

In the case of a sailboat which operates in a fluid environment bound by the water surface, an additional condition must be met:

3. zero net normal velocity at the water surface.

This condition is most easily satisfied by the method of images where a mirror image of the sail vortex lattice replaces the free surface (Figure 15).

In the preceding formulation, the inflow velocity was assumed to be uniform. This, however, does not accurately reflect real wind conditions, where the wind is slowed by viscous drag in the region near the water surface. The wind speed has been found experimentally to vary logarithmically
Figure 15: The method of images: the free surface is replaced by a mirror image of the sail vortex lattice.

with height [4], [14]. Given the wind speed at a height ten meters above the mean water surface, \( V(10) \), the wind speed at any height is given by:

\[
V(z) = 0.1086 \, V(10) \, \ln(304.8z) \tag{19}
\]

where \( z \) is some height above the water surface in feet [6]. Thus, the magnitude and direction of the inflow velocity vector changes with height. This has a direct bearing on the formulations for lift, (17), and drag, (18).

There is also a smaller indirect effect caused by the wind gradient. The greater inflow velocity at the top of the mast induces a spanwise velocity component analogous to a small amount of bound vorticity directed parallel to the free vorticity. For the height of the mast in this experiment, though, the wind gradient is not severe enough to make this term very significant.
At this point, it is important to note that there are two separate problems that can be solved using the vortex lattice method: the design problem and the analysis problem. In the former the sail loadings are defined by the designer and the shape that will produce them is desired. In the latter, the shape of the sail is defined, but the forces are desired.

The design problem is easily solved by using the design loading to solve for the Glauert coefficients of the fourier series expansion of the bound circulation [9]. In the case of a uniform flow, $U$, along the span, $s$, the desired lift and heeling moments are given in terms of these coefficients as:

$$L = \frac{N}{2} \rho U^2 s^2 a_1$$  \hspace{1cm} (20)$$

and

$$M = -\frac{N}{8} \rho U^2 s^3 a_2$$  \hspace{1cm} (21)$$

where $a_1$ and $a_2$ are the most significant coefficients in the fourier expansion of the circulation distribution:

$$\Gamma(y) = 2Us \sum_{n=2}^{\infty} a_n \sin(n\tilde{y})$$  \hspace{1cm} (22)$$

and $y$ is a spanwise variable such that:

$$y = \frac{s}{2} \cos(\tilde{y})$$  \hspace{1cm} (23)$$

The resulting circulation is then spread out along the chord, and the induced velocities at each control point can be calculated. The boundary condition of an impermeable, fixed
sail: zero net normal velocity at the control points, must be satisfied, implying that the sum of the induced velocity and the inflow velocity at the control point must run tangent to the sail surface. The slope of the resulting velocity vector therefore defines the slope of the sail at that point. Simple geometric manipulation then leads to the desired sailshape.

The analysis problem is, unfortunately, somewhat more difficult to solve. A set of simultaneous linear equations must be set up to satisfy the solid sail boundary condition at each of N control points and the Kutta condition at the trailing edge:

$$\sum_{n=1}^{M} A_{ij} \Gamma_j + v_i \cdot \hat{n} = 0$$

(24)

or, in matrix form,

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1N} \\ \vdots & \ddots & \vdots & & \vdots \\ a_{N1} & a_{N2} & a_{N3} & \cdots & a_{NN} \end{bmatrix} \begin{bmatrix} \Gamma_1 \\ \Gamma_2 \\ \Gamma_3 \\ \vdots \\ \Gamma_N \end{bmatrix} + \begin{bmatrix} v_1 \cdot \hat{n} \\ v_2 \cdot \hat{n} \\ v_3 \cdot \hat{n} \\ \vdots \end{bmatrix} = 0$$

(25)

where $A_{ij}$ is the matrix of influence coefficients that specify the normal velocity at control point $i$ induced by vortex $j$, and $v_i \cdot \hat{n}$ is the normal component of the inflow velocity at the same control point, $i$.

An additional complication is imposed by the need to consider the effect of the wake back on the sail. Since only
the geometry of the sail can be specified, the geometry of
the wake must also be determined analytically. The condition
that no force can be exerted on a vortex in the wake means
that the free vortices must be aligned with the flow
direction. The solution is obtained by first assuming some
arbitrary wake geometry and solving for the vortex
distribution, \( \Gamma(n) \). The local vortex sheet strength over
each panel is then used to calculate the induced velocity in
the wake and the geometry of the trailing vortices must be
redefined to align with the local flow. The process is
repeated until the geometry converges. Then the vortex sheet
strength is used to calculate the local tangential flow
velocity and thus local pressure above and below the sail
surface. The jump in pressure between pressure and suction
sides is integrated over the sail to give the total forces
generated by the sail.

The sail shapes measured by the video system were
analysed by this type of method. The vortex lattice code,
SVL4 developed by Greeley at Atlantic Applied Research Corp.
and described in [3] was used to calculate the forces
generated by the given sail shapes. This program follows the
above formulation for the analysis problem with several
noteworthy adaptations in paneling and wake alignment.

The first function of the SVL4 program takes the input
values of leading edge location, camber distribution, and
twist and uses B-splines to create a grid of horseshoe
vortices with user specified dimensions. Eighteen uniformly spaced segments were used spanwise, and eight cosine spaced segments were used chordwise for a total of 144 panels per sail. Cosine chordwise spacing was chosen as it has been shown to automatically satisfy the Kutta condition of zero flow around the trailing edge [3],[8]. Half height panels were used at the top and bottom of the span as they have been shown to improve accuracy. Once formed, the entire grid was rotated to account for heel.

The wind input (inflow) was specified by the apparent wind speed and angle as measured 10 feet above the mast head of the test boat. The VPP wind shear formulation [6] was then applied to calculate the inflow velocity and direction as a function of height, z:

\[
V(z) = \frac{0.6216 + 0.10861n(z)}{0.6216 + 0.10861n(z_0)} \times V(z_0)
\]  

(26)

where \(V(z_0)\) is the wind speed measured by a sensor at a height \(z_0\). This completed the description of the problem and solution of the distribution of circulation \(\Gamma(n)\) given a calculated matrix of influence coefficients, \(A_{ii}\) followed.

The wake alignment was accelerated [1], [2] by assuming that the trailing free vortices remained in their horizontal planes (no wake contraction) and that values of induced velocity in the wake could be interpolated from the velocities at the trailing edge and at some point far (1000
feet) down the wake by:

$$U_x(\xi,n) = U_{x_{TE}} + (U_{x_{ULT}}(n) - U_{x_{TE}}(n)) \cdot (3\xi - 3\xi^2 + \xi^3)$$ (27)

for:

$$\xi = \frac{s}{s_{ULT}} \quad s = \text{distance from trailing edge (TE)}$$

This formulation significantly cut computation time by accelerating convergence. The downwash at every point in the wake, as described above in (27), depends on only two points. The stability of the solution is greatly improved because only these two points need converge for the whole wake to converge. Estimating the downwash at each point in the wake rather than solving for it explicitly results in a significant reduction in computation time. A steady solution was reached within five iterations for each shape tested.

The results were available both as distributions of pressure jumps across the sail, and as integrated forces. Computation times for single iterations of four seconds for single sails and 10 seconds for main and jib combinations were recorded on the MIT Cray 2 supercomputer. These figures are believed to be nearly two orders of magnitude faster than those which could be obtained on a Vaxstation II.
5. Analysis of Sail Forces

Figure 17 shows a typical image processing result derived from the main only frame shown in Figure 16. The average apparent wind angle recorded during this run was 31.3 degrees. It is immediately obvious that something is amis considering the twist angle at the mast head exceeds this apparent wind angle. Consequently, the head must be backwinded. The video image, Figure 16, however, shows no sign of backwinding. The camber of a flexible sail would necessarily be inverted in this situation. Therefore, the results of the image process, especially the twist angles, are clearly inaccurate.

![Figure 16: View of main.](image)

A subsequent modification of the image system allowed direct measurement of known distances on the sail. The results revealed a rather consistent 20% error in lateral distances in the boat frame (vertically in the image) for the
Figure 17: Results from video image processing program for the image in Figure 16. LE_x and LE_y are the X and Y positions of the leading edge of each stripe. The first row of eleven numbers is the camber ratio (camber / chord) at eleven positions along the chord. The second row contains the corresponding full scale camber values. All angles are given in degrees, all lengths in feet.
mainsail camera. Longitudinal dimensions, however, appeared to be accurate to within a few percentage points. Evaluation of the jib camera view revealed a similar situation though the magnitude of the error was somewhat less (~10%).

This error has two likely sources. First, as can be seen in Figure 16, the calibration points are distributed broadly in the horizontal image direction but not in the vertical direction. Thus the camera calibration is based on a good range of points in the horizontal direction, but only on a very limited range vertically. The vertical distribution is too narrow to give a good characterization of the image as a whole. Secondly, all of the points are down at the edge of the image. In this region, the curvature of the lens leads to excessive distortion of the image. Therefore, the assumed mapping function (3) may not be particularly appropriate. The function was chosen because it is a very accurate representation of the image as a whole. It apparently breaks down when applied only within a limited area, i.e. the edge of the screen.

In an effort correct the mapping error, the twist and camber values were adjusted accordingly: Y-direction values were reduced 20% and twist angles were recomputed for each stripe. Several runs were also made keeping the camber the same but linearly varying the twist to achieve results that approached the experimentally measured forces. It is unclear whether the 20% correction applied to the image
results was sufficient or accurate, hence variations within a range of reasonable twist conditions provides a more general picture.

Variations in rig twist values were performed for each of the three cases: main only, jib only, and main and jib combined. Figures 18a-k describe the rig geometries considered in the analysis below. The wind conditions given are average values take over the duration of the corresponding test run.

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**Figure 18a: Sail input geometry for main only run 2a_3705**

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**Figure 18b: Sail input geometry for main only run 2a_3706**
### Figure 18c: Sail input geometry for main only run 2a_3707

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### Figure 18d: Sail input geometry for jib only run 11a_5079

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### Figure 18e: Sail input geometry for jib only run 11a_5080

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### Figure 18h: Sail input geometry for main and jib combined run 8a_444m.

** ** JIB **

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** JIB **

** SPAN (FT): 29.671 **

** Figure 18i: Sail input geometry for main and jib combined run 8a_444n. **

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<td>(FT)</td>
<td>(FT)</td>
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<td>(DEG)</td>
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** SPAN (FT): 36.543 **

** Figure 18j: Sail input geometry for main and jib combined run 8a_444o. **

** SPAN (FT): 29.671 **

** Figure 18k: Sail input geometry for main and jib combined run 8a_444o. **

46
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** JIB **

SPAN (FT): 29.671

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<th>Z AT LE (FT)</th>
<th>CHORD (FT)</th>
<th>TWIST (DEG)</th>
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<th>MAX. CAMBER (X/CHD)</th>
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<td>0.100</td>
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</table>

Figure 18k: Sail input geometry for main and jib combined run 8a_444p.

The inviscid assumption has important consequences for the modeling of real situations. Following the lifting line approach, the only source of drag, the induced drag, is the downwash induced by the trailing vortices. In the real world, however, viscosity plays a very real role. Viscosity leads to frictional drag between the fluid (in this case air) and the object (the sail). This drag source depends on the exposed area of the object, the material and surface properties, and the fluid flow speed. Viscosity also leads to the formation of turbulence and separation which cannot be modeled with potential based methods. The contributions of these sources, if estimated independently, can be
Figure 19: Coefficient of rig drag plotted against apparent wind angle based on the area of the jib.

...superimposed upon the inviscid theory solution to yield a more complete approximate model of the forces on sails. The drag due to the rigging was measured experimentally on the test boat for a range of apparent wind directions. The test was performed motoring in wide circles in the bare pole condition. The drag coefficient

$$\text{Cd} = \frac{\text{Drag}}{\frac{\rho}{2} V^2 A}$$

was calculated from the measured forces and plotted as a function of apparent wind angle. The results are plotted in Figure 19. The choice of area in the above nondimensionalization is very important. In this evaluation, the drag coefficients were calculated independently for each of the three sail configurations using the total sail. While the total drag due to the rigging in
each case was nearly identical (different wind speeds in each case) the coefficients vary between configurations by the ratio of their areas.

The coefficient of frictional drag due to the surface of the sails has been estimated by Milgram [9] to be in the range 0.04 to 0.05. A value of 0.05 was arbitrarily chosen for this analysis. This approximation is valid on the jib, but the presence of the mast directly in front of the main complicates matters. The mast disturbs the flow around the leading edge causing separation and bluff body drag. A systematic series of experiments on solid wing sections attached to circular and elliptical mast sections at the leading edge was conducted by Milgram [13]. For the relative mast and mainsail dimensions on the MIT test boat, the study suggests a drag coefficient of 0.12.

This value accounts for the contributions of the mast and mainsail but not the rigging (shrouds, stays, etc.). The drag on the rig was therefore estimated theoretically and the mast was found to account for ~50% of the total rig drag. The rigging component of the drag was subsequently approximated as half the experimentally measured rig drag.

Each of these additional drag terms is considered to act coincident with the apparent wind direction (as does the induced drag). Resolving the additional terms in the forward and side force directions yields the following corrections:
\[ F_x = F_{xi} - Df \cos B \]
\[ F_y = F_{yi} + Df \sin B \]  \( \text{(28)} \)

Where \( F_{xi}, F_{yi} \) are the invicid solution values of forward and side forces, and \( Df \) is the estimated viscous drag. Thus, any increase in drag translates directly into a decrease in the forward force and an increase in the side force.

The viscous drag coefficients used for each configuration appear in the table below:

<table>
<thead>
<tr>
<th>Drag Sources</th>
<th>sails</th>
<th>rigging</th>
<th>totals</th>
</tr>
</thead>
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<tr>
<td>main only</td>
<td>0.116</td>
<td>0.063</td>
<td>0.179</td>
</tr>
<tr>
<td>jib only</td>
<td>0.050</td>
<td>0.125</td>
<td>0.175</td>
</tr>
<tr>
<td>main and jib</td>
<td>0.086</td>
<td>0.057</td>
<td>0.143</td>
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</table>

Table 2: Coefficients of viscous drag used as estimates of the frictional drag in each of the sail configurations. The coefficients were calculated based on the total sail area of the corresponding configuration.

The results of the SVL4 program for each of the runs is presented in Figures 23 - 33 at the end of this chapter. The input sail shape and resulting pressure distribution are plotted and the resulting forces are tabulated for the inviscid solution. Discussion of the result of each configuration summarized in Figure 20 follows.
In the case of the main sail only, inviscid theory clearly over predicts the attainable forward force by more than double. Even after the superposition of rig drag, the forward forces do not agree. The side forces are, however, in much better agreement, so a quick check of the models validity is warranted.

<table>
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<th>Main Only Results:</th>
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<th>AWA</th>
<th>Fxi</th>
<th>Fyi</th>
<th>Df</th>
<th>Fx</th>
<th>Fy</th>
<th>Fx/Fy</th>
</tr>
</thead>
<tbody>
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<td>35.15</td>
<td>163.34</td>
<td>299.91</td>
<td>38.93</td>
<td>131.51</td>
<td>322.32</td>
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<tr>
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<td>35.15</td>
<td>154.45</td>
<td>278.73</td>
<td>38.93</td>
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<td>108.51</td>
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<th>AWA</th>
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<th>Fyi</th>
<th>Df</th>
<th>Fx</th>
<th>Fy</th>
<th>Fx/Fy</th>
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<td>102.60</td>
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<td>0.36</td>
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<tr>
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<tr>
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<th>AWA</th>
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</table>

Figure 20: Results comparing calculated forces both with and without the frictional component to the experimental result. AWS and AWA are the apparent wind speed and angle. As before, Fxi and Fyi are inviscid theory solutions for the forward and side forces, Fx and Fy are the corresponding values after superimposing the frictional drag, Df. Fx/Fy is simply the ratio of forward to side force. The final row in each group is the experimental result.
Figure 21 compares the ratio of forward force to side force for both the inviscid and drag included cases to those reported for a similar case in the SNAME T & R Report "Sail Force Coefficients for Systematic Rig Variations" [11]. Both ratios are quite similar which certainly supports the validity of the SVL4 formulation.

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T & R Report R-10:

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Figure 21: Check of SVL4 results against reported values.

The experimental forward and side force results fall within the range of previously recorded values, so they must be assumed correct. Therefore, the influence of the mast on the aerodynamics of the main sail must be greater than predicted. In Figure 22, the calculated lift and frictional drag have been adjusted to bring the forward forces of experiment and theory into agreement. Interestingly, only by simultaneously manipulating both the lift and the drag (decreasing the former 13% and doubling the latter) can the
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<th>Fy1</th>
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<th>Fy1</th>
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</tr>
<tr>
<td>2a_3706</td>
<td>16.31</td>
<td>35.15</td>
<td>139.53</td>
<td>244.66</td>
<td>77.85</td>
<td>75.85</td>
<td>289.48</td>
<td>0.26</td>
</tr>
<tr>
<td>2a_3707</td>
<td>16.31</td>
<td>35.15</td>
<td>126.54</td>
<td>218.17</td>
<td>77.85</td>
<td>62.86</td>
<td>262.99</td>
<td>0.24</td>
</tr>
<tr>
<td>Corresponding experimental results</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>62.05</td>
<td>259.05</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Figure 22: Manipulation of the lift and drag to improve agreement with the experimental results.

side force also be brought into agreement. The significance of this discrepancy is not yet understood.

In the jib only case, the agreement between the inviscid and experimental results is also rather poor. The inclusion of the frictional drag though brings the results reasonably close. This is certainly expected since, of all the sails, the jib is the most like a thin sheet and is most closely modeled by vortex lattice theory.

The SVL4 results for the main and jib combined are also very close to the experimental results when the frictional drag terms are added. The improvement in the predictive accuracy of the vortex lattice method in this case over that
for the main only is likely due to the influence of the jib on the air flow over the mast. The circulation around the jib acts to reduce the inlow angle at the mast. This could reduce the drag contribution of the mast flow separation to the overall sail system.

It is apparent that predicting absolute sailforces using invicid theory models is of questionable value. There are far too many variables and uncertainties to be able to construct a truely all inclusive model with results that will match those measured on the test boat. However, there is a great deal of information that still can be learned by applying invicid models to sail shapes and examining the results in a relative sense. A computer-based model such as the SVL4 program can be used to compare several different sail or to examine the effects that varying a single sail's shape can have.

Each case in Figure 20 illustrates the range of forces that can attained with the same sail through manipulation of the shape. By examining results such as these the designer can gain greater insight into shaping sails and the sailor into trimming sails.
Main Only Results:

<table>
<thead>
<tr>
<th>2a_3705</th>
<th>Lift</th>
<th>Drag</th>
<th>Fx</th>
<th>Fy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main</td>
<td>339.29</td>
<td>39.11</td>
<td>163.34</td>
<td>299.91</td>
</tr>
</tbody>
</table>

Figure 23: SVL4 vortex lattice results for the main only test 2a_3705: sail geometry (a), pressure distribution (b), and dimensional force results (c).
Main Only Results:

<table>
<thead>
<tr>
<th>2a_3706</th>
<th>Lift</th>
<th>Drag</th>
<th>Fx</th>
<th>Fy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main</td>
<td>316.82</td>
<td>34.18</td>
<td>154.44</td>
<td>278.73</td>
</tr>
</tbody>
</table>

Figure 24: SVL4 vortex lattice results for the main only test 2a_3706: sail geometry (a), pressure distribution (b), and dimensional force results (c).
Figure 25: SVL4 vortex lattice results for the main only test 2a_3707: sail geometry (a), pressure distribution (b), and dimensional force results (c).
Jib Only Results:

<table>
<thead>
<tr>
<th>11a_5079</th>
<th>Lift</th>
<th>Drag</th>
<th>Fx</th>
<th>Fy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jib</td>
<td>203.82</td>
<td>36.71</td>
<td>97.54</td>
<td>182.68</td>
</tr>
</tbody>
</table>

Figure 29: SVL4 vortex lattice results for the jib only test 11a_5079: sail geometry (a), pressure distribution (b), and dimensional force results (c).
Figure 30: SVL4 vortex lattice results for the jib only test 11a_5080: sail geometry (a), pressure distribution (b), and dimensional results (c).
Figure 31: SVL4 vortex lattice results for the jib only test 11a_5081: sail geometry (a), pressure distribution (b), and dimensional force results (c).

<table>
<thead>
<tr>
<th></th>
<th>Lift</th>
<th>Drag</th>
<th>Fx</th>
<th>Fy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jib</td>
<td>208.85</td>
<td>39.34</td>
<td>98.60</td>
<td>188.27</td>
</tr>
</tbody>
</table>
Figure 32: SVLA vortex lattice results for the jib only test 11a_5082: sail geometry (a), pressure distribution (b), and dimensional force results (c).
Main and Jib Results:

<table>
<thead>
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<th>Drag</th>
<th>Fx</th>
<th>Fy</th>
</tr>
</thead>
<tbody>
<tr>
<td>8a_444m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main</td>
<td>277.32</td>
<td>92.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jib</td>
<td>136.43</td>
<td>-0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>415.75</td>
<td>92.04</td>
<td>136.28</td>
<td>403.42</td>
</tr>
</tbody>
</table>

Figure 33: SVL4 vortex lattice results for the jib and main combined test, 8a_444m: sail geometry (a), pressure distribution (b), and dimensional forces (c).
Main and Jib Results:

<table>
<thead>
<tr>
<th></th>
<th>Lift</th>
<th>Drag</th>
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<th>Fy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main</td>
<td>281.06</td>
<td>90.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jib</td>
<td>126.72</td>
<td>-0.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>407.77</td>
<td>89.78</td>
<td>134.09</td>
<td>395.42</td>
</tr>
</tbody>
</table>

Figure 33: SVL4 vortex lattice results for the jib and main combined test, 8a_444n: sail geometry (a), pressure distribution (b), and dimensional forces (c).
Main and Jib Results:

<table>
<thead>
<tr>
<th></th>
<th>Lift</th>
<th>Drag</th>
<th>Fx</th>
<th>Fy</th>
</tr>
</thead>
<tbody>
<tr>
<td>8a_444o</td>
<td>198.62</td>
<td>54.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main</td>
<td>198.62</td>
<td>54.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jib</td>
<td>135.92</td>
<td>0.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>334.53</td>
<td>55.07</td>
<td>125.91</td>
<td>314.79</td>
</tr>
</tbody>
</table>

Figure 33: SVL4 vortex lattice results for the jib and main combined test, 8a_444o: sail geometry (a), pressure distribution (b), and dimensional forces (c).
Main and Jib Results:

<table>
<thead>
<tr>
<th>8a_444p</th>
<th>Lift</th>
<th>Drag</th>
<th>Fx</th>
<th>Fy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main</td>
<td>204.21</td>
<td>53.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jib</td>
<td>124.07</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>328.27</td>
<td>53.71</td>
<td>123.64</td>
<td>308.73</td>
</tr>
</tbody>
</table>

Figure 33: SVL4 vortex lattice results for the jib and main combined test, 8a_444p: sail geometry (a), pressure distribution (b), and dimensional forces (c).
6. Conclusions

The video system, as implemented, can transfer actual sail shape images to a personal computer for processing. However, limitations were imposed on the system's accuracy by the non-ideal optical behavior inherent in any real video camera. Distortion of the video image is worst at the edges due to the curvature of the lens. It is at the edges that most calibration schemes run into trouble. An unfortunate consequence of the camera orientation was that the calibration marks (in the cross-vessel direction) were too close to each other (due to the narrow test boat deck) and too close to the edge of the image. In the future, a wider angle lens can be used. This will allow a less extreme camera orientation -- one that will bring the calibration marks closer to the center of the image. This can make a dramatic improvement in the accuracy of the image to world mapping function.

Mounting the cameras in the deck can eliminate this problem altogether. Since the cameras would remain fixed in the boat reference frame (neglecting flexure of the hull and deck) the calibration will not change with time. Therefore, the cameras can be calibrated once very accurately in the laboratory and then installed. Of course, periodic recalibration may be necessary given the conditions the cameras will operate in.
Difficulties in following stripes can be corrected through a combination of techniques. Image filtering and contrast enhancement would serve to clarify the stripe and improve the scheme's stability. However, this would come at the expense of computation time. As computer power increases with advancing technology, more sophisticated techniques for stripe detection can be implemented.

More robust following schemes including filtering of the projected stripe locations are more likely to give favorable results over the greatest range of conditions. Such techniques as Kalman and other adaptive filters have been successfully implemented in other video applications [15] and [17]. These schemes can be designed to work in windowed areas of interest, thus they can be arranged to require a minimum of computation time.

On the whole, video image processing has a great potential in marine applications. This project has shown that video systems are easily integrated with personal computers to create powerful, yet low cost measurement tools.

The results of comparing experimentally measured sail forces to those predicted by the vortex lattice method were generally favorable. The comparisons clearly show that the inclusion of viscous effects (friction and form drag) are vital to the predictive accuracy of the inviscid model. This result is important in both the analysis and design situations.
The comparisons also show that current estimates of the influence of the mast on the aerodynamics of the main sail are inadequate in the absence of a jib. In this case the magnitude of the viscous forces and the unpredictable nature of the flow around the mast make it unwise to apply inviscid theory based models, such as vortex lattice, alone. This result is really only of interest to designers of cat-rigged boats such as most single handed classes and some high performance catamarans since the presence of a sizable jib apparently modifies the flow sufficiently to allow standard drag formulations.

Inviscid theory models are clearly too sensitive to give accurate absolute results. It is impossible to calculate explicitly the contribution of every source of drag and flow instability to the aerodynamic performance of sails. For this reason, vortex lattice theory and the like will prove to be most powerful when used to examine relative performance. The characteristics of similar sails be compared to evaluate design changes, for example. The computer-based models will find their greatest utility in this capacity.
References


