Simple Multilayer Panel Method for Partially Separated Flows Around Two-Dimensional Masts and Sails

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Abstract

A NEW multilayer panel method has been developed using superimposed combinations of vortex doublet and source/sink elements to predict the static pressure distributions found over two-dimensional mast/sail geometries. The method takes into account all the partially separated regions present, and all the computations are performed without any need for iteration. The only inputs required are: mast/sail geometry, aerodynamic incidence angle, freestream Reynolds number, and empirically determined separation and reattachment locations. All of the base pressures involved are obtained as part of the solution. Comparison between experimental and theoretical results showed excellent agreement.

Contents

Sail makers and yacht designers have long sought a method for accurately predicting the aerodynamic forces generated by complete sailing rigs. The problem, however, is an extremely complicated one, involving many interacting aerodynamic, aeroelastic and hydrodynamic factors. Because of the complex nature of the sailing yacht configuration, previous researchers have tended to concentrate on isolated aspects of the overall problem, with the intention of contributing towards a set of building block solutions that offer the promise of being combined together in the future. In accordance with this general approach the present work addresses the single problem of mast/sail aerodynamic interaction, by attempting to develop a theoretical means of accurately predicting static pressure distributions over sail-like geometries in the presence of leading-edge obstructions (masts).

Before any theoretical formulations were attempted, an in-depth experimental study was undertaken in Ref. 1, with testing limited to two-dimensional flows and circular section masts only. The surface static pressure distributions obtained for the various representative combinations of mast/sail geometries tested all conformed to a "Universal Distribution" shape of the type shown in Fig. 1, which was highly influenced by areas of partially separated flow.

The method adopted for the present work addressed the problem simply by accurately modeling only the experimentally observed conditions on the solid mast and sail surfaces, with no attempt made to locate any off-body streamlines or to simulate the wake.

To create a representative model, the following surface boundary conditions had to be satisfied:

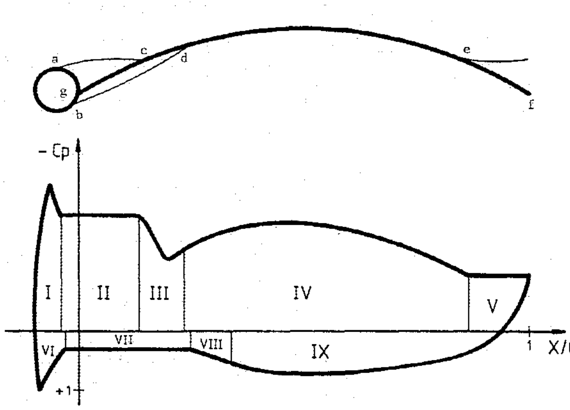
1) No fluid could cross the solid mast or sail surfaces (flow tangency, or no net inflow condition).

2) Mast and trailing-edge separation had to occur tangentially, including fluid leaving the lower surface at the trailing edge (Kutta condition).

3) Surface pressures within separated base-pressure regions had to be constant and equal to that existing at the point of separation in each case. This negated any need for an empirical base-pressure input.

To model these surface boundary conditions, a continuous sheet of vorticity was used to simulate the solid mast/sail surfaces, while source sheets were introduced to model the bubble and trailing-edge separation regions in the manner shown in Fig. 2. In order for such a tri-layer singularity sheet combination to be solvable, it was necessary to consider the source sheets representing the constant pressure boundary conditions on the upper and lower sail surfaces behind the mast, as two separate sheets. Also, for the purposes of applying the boundary conditions, it was essential that the source sheets be considered displaced slightly above or below the vortex sheet, as again indicated by Fig. 2, although in the actual mathematical model all three sheets occupied the same space along the mast/sail contours.

To numerically model the vortex and source sheets, vortex doublet and source/sink doublet panels were used, respectively. The latter have the advantage of mass conservation, making them ideal for modeling enclosed bubble regions.



REGION	DESCRIPTION
I	Upper Mast Attached Flow Region
II	Upper Separation Bubble
III	Upper Reattachment Region
IV	Upper Aerofoil Attached Flow Region
V	Trailing Edge Separation Region
VI	Lower Mast Attached Flow Region
VII	Lower Separation Bubble
VIII	Lower Reattachment Region
IX	Lower Aerofoil Attached Flow Region

Fig. 1 Universal pressure distribution.

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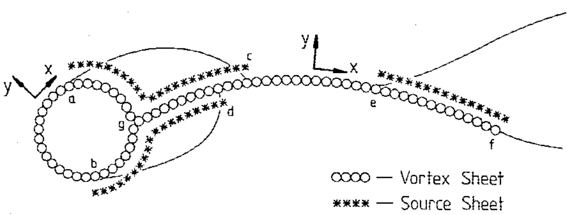

Fig. 2 Sheet layout for mast/sail model.

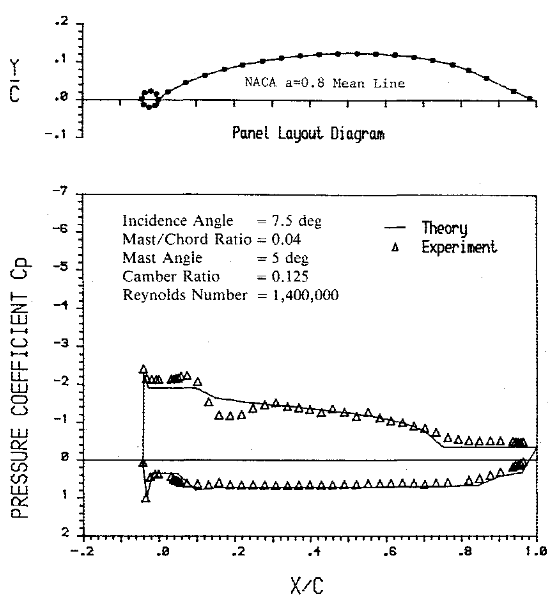

Fig. 3 Comparison of experimental[1] and computed static pressure distributions.

Using the curvilinear surface-fitted x-y axes shown in Fig. 2, a multilayered combination of vortex and source doublet panels were introduced into a uniform flowfield along the surface contours of the mast/sail geometry to be simulated. Empirically determined separation and reattachment locations were required at this stage to define the start and finish locations of the overlayered source doublet panels. For validating the present method these locations were taken from the extensive experimental data of Ref. 1. Although this need for empirical data represents a severe limitation on the applicability of the method, techniques of this type offer the possibility of being iteratively coupled with viscous boundary layer calculations, thereby removing the need for empirical input.

For any of the vortex doublet panels representing the solid mast/sail surfaces, the normal component of velocity present at each control point k was due to the freestream U_y, all vortex and source doublet panels in the flowfield u_{yj}^v and u_{yj}^s, the local normal velocity in the negative y direction due to the upper surface source sheet $-\Delta u_y$, and the local normal velocity in the positive y direction due to the lower surface source sheet $+\Delta u_y$. This normal velocity component had to be zero to satisfy boundary condition 1, i.e.,

$$u_{yk} = \left(U_y + \sum_{j=1}^{m} u_{yj}^v + \sum_{j=1}^{n} u_{yj}^s \right)_k - \Delta u_{yL} + \Delta u_{yLL} = 0 \quad (1)$$

where L represents the source doublet panel directly above the vortex doublet panel k and LL is the source doublet panel directly below panel k. For those panels k where L and/or LL did not exist, Δu_{yL} and/or Δu_{yLL} were zero, respectively. The total number of vortex and source panels used are m and n, respectively.

Similarly, for any source doublet panel-control point k, the surface tangential velocity component (in the surface-fitted x-direction) is given by

$$u_{xk} = \left(U_x + \sum_{j=1}^{m} u_{xj}^v + \sum_{j=1}^{n} u_{xj}^s \right)_k + (-)\, \Delta u_{xL} \quad (2)$$

where L is used this time to represent the vortex doublet panel directly below (or above) the source panel considered at k.

It should be noted that in overlaying the source doublet panels throughout the various constant-pressure regions, the first panel in each region (that representing the point of separation) was left as a single vortex doublet panel with no overlay. This helped to satisfy boundary condition 2 concerning the smooth detachment of the separated free streamlines.

An equation could therefore be derived for the tangential velocity at any of the three separation points k = sep:

$$u_{x\text{sep}} = \left(U_x + \sum_{j=1}^{m} u_{xj}^v + \sum_{j=1}^{n} u_{xj}^s \pm \Delta u_x \right)_{\text{sep}} \quad (3)$$

The boundary condition required within separation regions was that of constant pressure (and therefore tangential velocity) equal to that at separation, and so it was this that had to be applied to each of the source doublet panel control points. Enforcing this condition was easily achieved by equating together Eqs. (2) and (3). Using Eqs. (1)–(3) it was possible to formulate a boundary-condition expression at each control point in the flowfield in terms of the unknown panel strengths, aerodynamic constants, and mast/sail geometry. These equations could be expressed in the following form:

$$G_k = \sum_{j=1}^{m} Q_{jk}\, \mu_j + \sum_{j=1}^{n} W_{jk} M_j \quad (4)$$

where Q_{jk} and W_{jk} are influence coefficients dependent entirely on geometry, G_k is a constant for any control point k and is dependent on geometry and freestream velocity, and μ_j and M_j are the unknown vortex and source doublet panel strengths.

The resulting set of simultaneous equations was solved for the unknown panel strengths using a regular library equation-solving routine. No iterations were required and the panel strengths so obtained were used in Eq. (2) to give the tangential velocity components, and hence the static pressure coefficients over the mast/sail surfaces.

In order to determine the accuracy of the present theory, several comparisons were made with the experimental data of Ref. 1. From the single example presented in Fig. 3, it can be seen that the agreement between theory and experiment was excellent, even though a relatively coarse panel layout of only 45 panels was used in the model.

Only eight panels were used to model the mast, making it difficult to accurately define the separation locations; however, despite this, the separation base pressures were all predicted very well.

The method was not able to accurately model the reattachment regions (III and VIII in Fig. 1), essentially because neither the flow tangency or constant-pressure boundary conditions were truly applicable to these regions.

References

[1]Wilkinson, S., "Partially Separated Flow Around 2D Masts and Sails," Ph.D. Thesis, Ship Science Dept., Univ. of Southampton, Southampton, U.K., 1984.