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TECHNICAL MANUAL AND USER GUIDE FOR THE SURFACE PANEL CODE: PALISUPAN

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Technical Manual and User Guide

for the Surface Panel Code:

PALISUPAN

by

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USER GUIDE

PArallel LIfting SUrface PAnel code

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Summary

This report describes the theoretical background and the method of use of a general purpose lifting surface panel code Palisupan. This code, originally developed in Occam for use across arrays of transputers, has been rewritten in ANSI C and a serial version is available for use on Unix based machines. The code uses dynamic memory allocation to maximise the available problem size for a given computational environment. The two available methods for preparing geometry definition files are described as are the production of various types of post-processing information. A section describes the importance of the validation process. An exercise in the form of a validation tutorial introduces the user to the limitations of three-dimensional potential flow analysis using a surface panel code. A final section describes an assignment for users to implement in order to develop increased familarity with the solution of a practical design problem. In this case the analysis of yacht keel-bulb hydrodynamic performance.

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Nomenclature

ϕ	Disturbance Potential
σ	Source Strength
μ	Dipole strength
ω	Angular Velocity
n	Unit normal vector
c	Rudder chord
r	Radial position vector (x, y, z)
s	Rudder span
v	Velocity (u, v, w)
Cp	Surface pressure coefficient, $1-V^2/V_\infty^2$
C_L	Non-dimensional Lift Coefficient, $L/1/2\,\rho V_\infty^2 sc$
C_l	Sectional Lift Coefficient, $l/1/2\,\rho V_\infty^2 c$

1.0 Introduction

This document presents guidance as to the use of the general purpose surface panel code PALISUPAN. The program solves potential flow around arbitrary three-dimensional bodies by mapping quadrilateral panels over the body surfaces and using a boundary element approach to determine the dipole potential strength associated with each panel. Numerical differentiation of the surface potential allows the surface pressure distribution and hence total body force to be determined. The program incorporates a powerful surface geometry definition process which allows considerable flexibility and provides a rapid method of defining geometries for investigation.

This user manual describes the background to the development of the code and a brief description of the associated fluid dynamic theory. For a far fuller description of the theory and development of surface panel codes the reader is referred to Ref [1].

The actual use of the program is straightforward. The preparation of the geometry definition files and analysis and processing of the results is described as it is these stages of the process which require the most effort to ensure an accurate analysis.

If used correctly, surface panel codes are a powerful analysis tool. However, by its nature, the assumption of potential flow neglects the influence of viscosity on the flow around bodies. At high Reynolds numbers the influence of fluid viscosity is confined to a thin layer (boundary layer) next to the body surface and a region of shed vorticity (wake) behind a body. These regions can have an important effect on the pressure distribution around a body, and hence total force acting, and also if sufficiently severe an adverse pressure gradient can induce flow separation and fundamentally alter the flow regime around a body. It is essential that these possible discrepancies can be identified and their effects on the potential solution accounted for. It is in this context that the final section of the manual describes the process of code validation and how much assurance the user can place on the results obtained

2.0 History

Palisupan was developed in order to study theoretically the interaction between a ship rudder and propeller. In addition, the program was used as a testbed for investigating the performance of parallel computers in solving an implicit algorithm. In particular, PALISUPAN was initially written in Occam2 a computer language developed to exploit the full capabilities of transputer based computers.

Code development was mainly carried out on the Department of Ship Science's network of five transputers. The main foundations of the code were written during the summer of 1990. Verification of the theoretical method for modelling ship rudders and propellers was completed by February 1993 and submitted as part of a PhD Thesis (Ref[2]).

The status of the code remained relatively fixed and was used as part of the work of a number of undergraduate, diploma, and M.Sc. student projects (Refs[3,4,5,6,7,8]). In the summer of 1995, as part of the IBM SUR project, the code was translated from Occam2 into Ansi C in order to exploit the capabilities of the 16 node SP2 computer. As part of this process a sequential version was developed which can be compiled and then run either on Unix workstations or on PC 's.

3.0 Theory

In a lifting surface panel formulation the approximation of the full Navier-Stokes equation assumes that the flow is inviscid, incompressible and irrotational and satisfies Laplace's potential equation:

$$\nabla^2 \phi = 0 \qquad [1]$$

A detailed description of the method and a review of its historical development is given by Hess[9]. Lamb[10] showed that a quantity satisfying Laplace's equation can be written as an integral over the bounding surface S of a source distribution per unit area s and a normal dipole distribution per unit area m distributed over the S. If **v** represents the disturbance velocity field due to the bounding surface (or body) and is defined as the difference between the local velocity at a point and that due to the free-stream velocity then:

$$\underline{v} = \nabla \phi \qquad [2]$$

where ϕ is defined as the disturbance potential. This can be expressed in terms of a surface integral as:

$$\phi = \int\int_{S_B} \left[\frac{1}{r}\sigma + \frac{\partial}{\partial n}\left(\frac{1}{r}\right)\mu\right] dS + \int\int_{S_W} \frac{\partial}{\partial n}\left(\frac{1}{r}\right)\mu \, dS \qquad [3]$$

where S_B is the surface of the body and S_W a trailing wake sheet. In the expression r is the distance from the point for which the potential is being determined to the integration point on the surface and $\partial/\partial n$ is a partial derivative in the direction normal to the local surface. A dipole distribution is used to represent the wake sheet. Hess [11] showed this can be directly related to the vorticity distribution used in vortex lattice methods (VLM).

The conditions imposed on the disturbance potential are that (from Hess[9]):

1) the velocity potential satisfies Laplace's equation everywhere outside of the body and wake;
2) the disturbance potential due to the body vanishes at infinity;
3) the normal component of velocity is zero on the body surface;
4) the Kutta-Joukowsky condition of a finite velocity at the body trailing edge is satisfied.
5) the trailing wake sheet is a stream surface with equal pressure either side.

For a steady-state solution the wake dipole strength distribution is uniquely determined by the application of the Kutta condition at the body trailing edge. As conditions (1) and (2) are satisfied as functions of μ and σ, conditions (3) and (4) are used to determine μ and σ on the body. The Kutta condition only applies at the trailing edge and some other relationship has to be used to uniquely determine the distribution of μ and σ over the body. The numerical resolution of this non-uniqueness is referred to as the singularity mix of the lifting-surface method.

Lee[12] carried out a two-dimensional investigation into four possible schemes for the solution of Lamb's equation. The conclusion of that study was, that for lifting surfaces which have both thin and thick sections (e.g. propeller blades), the perturbation potential method taken from the work by Morino and Kuo[13] was the most suitable. The principal advantages of this method are that because panel potential (scalar) rather than velocity (vector) influence coefficients are calculated only a third of the memory requirement for the method is needed. Also, the perturbation potential influence coefficient is an order less singular. Kerwin and Lee [16] used this method and found it robust in their investigation of ducted propellers.

Morino's numerical procedure is based on representing the body surface by a series of N quadrilateral panels each with an unknown but constant dipole strength per unit area. The vertices of these panels are located on the actual surface of the body. The wake sheet is represented by M panels placed on the stream-surface from the trailing edge of the body surface. Its dipole strength per unit area is related to the difference in dipole potential at the trailing edge. In Morino's work the wake strength m_w was equated to the difference in potential between the upper and lower surface at the trailing edge.

That is:

$$\mu_\omega = \phi_\upsilon - \phi_l \qquad [4]$$

On the body surface the source strength per unit area is prescribed by satisfying the condition for zero normal velocity at the panel centroid:

$$\sigma_s = \overline{U} \,.\, \overline{n} \qquad [5]$$

where **n** is the unit normal outward from the panel surface and U the specified inflow velocity at the panel centroid.

The numerical discretisation of Eqn[3] gives the potential at the centroid of panel i as:

$$\phi_i = \frac{1}{2\pi}\sum_{j=1}^{N}\left(\left(\mathrm{U}_\infty \cdot \mathrm{n}_j\right)S_{ij} - \phi_j D_{ij}\right) + \sum_{k=1}^{M}\Delta\phi_k W_{ik} \qquad [6]$$

where for panel j:
S_{ij} is the source influence coefficient of a unit strength panel;
D_{ij} the dipole influence coefficient;
W_{ik} the influence of the constant strength wake strip extending to infinity.

As there are N independent equations corresponding to the N body surface panel centroids, Eqn[6] is closed and can be evaluated. Expressed in matrix form it becomes:

$$[D_{ij}]\phi + [W_{ik}]\Delta\phi = [S_{ij}](U_\infty \cdot n) \qquad [7]$$

For Morino's original trailing edge Kutta condition, which directly relates $\Delta\phi$ to the difference in trailing edge panel potential, the matrix expression [7] can then be directly solved to give the vector of dipole potentials ϕ. Numerical differentiation of dipole potential along the body surface allows the surface velocity and hence pressures on the surface to be evaluated.

4.0 Newman Panel

At the heart of a lifting surface panel method is the efficient calculation of the potential (or velocity) influence coefficients at a field point due to a particular panel's source or dipole distribution. Newman[12] derived expressions for calculating the exact influence coefficients of a constant strength distribution of sources and normal dipoles over a quadrilateral panel. The method of calculation of the dipole influence coefficient avoids the use of numerical integration. The approach of Newman was different from that used originally by Hess and Smith[8] although the form of the exact source influence coefficient is algebraically similar.

As the distance of the field point from the panel centroid increases approximate expressions are used for the influence coefficients to reduce computational effort. Following Hess & Smith, Newman also gives arbitrary order multi-pole expansions. These ensure that at greater distances from the panel the accuracy of the source and dipole influence coefficient is maintained while at the same time the computational time is reduced.

The modelling of the interaction requires the evaluation of total velocity in the field domain away from the lifting surface. The expressions given by Newman are for the potential influence only. For potential flow, the velocity is the local gradient of the potential. Therefore, the velocity influence due to a panel has been derived by applying the Grad operator ∇ to the source and dipole influence expressions.

5.0 Kutta condition

For a steady-state solution, the dipole strength of the trailing wake sheet has a constant strength in the stream-wise direction. This strength is directly related to the circulation around the lifting surface. The original Kutta condition, implemented by Morino, involved setting the trailing wake sheet dipole strength equal to that of the difference in perturbation potential at the trailing edge. This implies that the pressure difference at the trailing edge would be close to zero. Lee showed that a source term should also be included to ensure that there was zero difference in total potential caused by the difference in source strength of the two trailing edge panels and gave the expression for this as

$$\Phi_s = U_o \cdot r \qquad [8]$$

For three-dimensional flow, **r** is the vector between the centroids of the two trailing edge panels. With this additional term, when significant cross-flow occurs at the trailing edge, the upper and lower panels will not necessarily be at the same pressure and a non-physical trailing edge pressure loading occurs. This was seen by Lee as the need to explicitly equate the upper and lower panel pressure using an iterative scheme to correct the dipole wake strength based on a factor K multiplying the pressure loading at the trailing edge from the previous iteration.

The method developed in this work uses the description given in [10,16] as a basis. An explicit condition of no pressure loading is enforced across the upper and lower trailing edge panels. That is, the pressures are equal:

$$\Delta p_{te} = p_u - p_l = 0 \qquad [9]$$

If it is assumed that ΔCp is primarily a function of the local trailing edge wake sheet strength $\Delta\phi$ an iterative Newton-Raphson approach is suggested to determine the wake strength for the point of zero pressure difference at the trailing edge. That is:

$$\Delta\phi^k = \Delta\phi^{k-1} - \frac{\Delta p(\Delta\phi^{k-1})}{\frac{d\Delta p}{d\Delta\phi}} \qquad [10]$$

where the trailing edge pressure loading Δp is the difference in pressure between the upper and lower panels at the trailing edge and Lee's K is the inverse of the derivative of Δp with respect to the wake strength $\Delta\phi$.

$$\Delta p = p_U - p_L \qquad [11]$$

Substituting for pressure in terms of surface velocity **V** gives

$$\Delta p = (V_L \cdot V_L) - (V_U \cdot V_U) \qquad [12]$$

Differentiating [12] with respect to a change in wake strength $\Delta\phi$ gives

$$\frac{d\Delta p}{d\Delta\phi} = 2\left(V_L \cdot \frac{dV_L}{d\Delta\phi} - V_U \cdot \frac{dV_U}{d\Delta\phi}\right) = \left(\frac{1}{K}\right) \qquad [13]$$

By deriving an expression for surface velocity in terms of the velocity influence sum of all the source and dipole panels, and wake strips and then differentiating with respect to the wake sheet strength and assuming that the principal influence on a pair of trailing edge panel's is due to the attached wake strip then $\mathbf{dV}/d\Delta\phi$ can be expressed as:

$$\frac{dV_L}{d\Delta\phi} = V_{WL} \quad and \quad \frac{dV_U}{d\Delta\phi} = V_{WU} \qquad [14]$$

where $\mathbf{V}_{WL}$ and $\mathbf{V}_{WU}$ are the velocity influence coefficients of the wake strip attached to the panels at their respective centroids. All the components can then be numerically evaluated and hence the wake strength updated.

The zero'th order (k=0) approximation for the wake strength is taken to be the original Morino kutta condition:

$$\Delta\phi^0 = \phi_u - \phi_l \qquad [15]$$

as ϕ_u and ϕ_l are unknown then the numerical Eqn[7] is arranged with the unknowns on the left hand side:

$$\left[D_{ij} + W_{ik}\right]\phi = \left[S_{ij}\right](U_\infty \cdot n) \qquad [16]$$

Once the solution vector f is obtained this is used to calculate ΔCp at the trailing edge. Using Eqn[10] the correction to the wake strength is found. This correction vector of known strength is multiplied by the wake strip influence coefficient matrix W_{ik} and applied to the right hand side of the equation. This modifies Morino's original matrix expression to:

$$[\,D_{ij} + W_{ik}\,]\,\phi = [\,S_{ij}\,]U_\infty \cdot n_j - [\,W_{ik}\,]\left(\frac{d\Delta\phi}{d\Delta p}\Delta p\right)^k \qquad [17]$$

The process is repeated until the pressure loading at the trailing edge has been removed to any significant degree.

6.0 Geometrical Definition

6.1 Original

An accurate geometrical definition of a three-dimensional body as a closed surface constructed from quadrilateral elements is a crucial component of a lifting-surface analysis. How easily arbitrary bodies can be defined will determine the usefulness of a numerical analysis code. Lee [16] tailored the flow solver for a particular geometry e.g. semi-span wing or propeller blade. This approach is of limited use and a better approach is that where an input file is used which contains the four vertices for each panel. The preparation of this pre-processing file is time consuming as a new file has to be created for every change in panelling density. However, such an input file format allows arbitrary bodies to be tested without recourse to creating individual executable code for every geometry.

In the origins of PALISUPAN one of the principal features was the investigation of the performance of a lifting-surface code on a transputer network. Therefore, it was necessary to have a simple means of scaling the overall problem size by altering the number of panels used to define a lifting-surface. Therefore, the decision was made to combine the two approaches described and generate the actual panel vertex coordinates within the program but use a pre-processing file to define the number of bodies and their individual geometry. This allows a problem to be scaled by using the internal panel generator to produce a different number of panels for the same overall body geometry.

A variety of means are available for defining a three-dimensional surface (or body). A ship hull form is conventionally defined using a series of lines which lie in parallel planes. These lines, whether waterlines, buttocklines or transverse sections, are themselves defined in terms of an ordered set of coordinates. A mathematical relationship is then used to generate the curved lines between the coordinates and hence specify a three-dimensional surface.

An extremely useful and straightforward means of relating the line coordinates to the curve passing through them is that of a parametric cubic spline procedure. A spline approximation is defined as a piece-wise polynomial approximation to a curve. Each segment of a line is represented as a polynomial. For a cubic spline at the end of each segment the gradient and curvature of the polynomial expression are matched to the adjoining polynomial expressions. This results in a curve made up of a series of cubic lines i.e.

$$y = k_1 t^3 + k_2 t^2 + k_3 t + k_4 \qquad [18]$$

where the values of the constants k_1,k_2,k_3 and k_4 are solved using the end conditions of gradient and curvature continuity. Defining a value of the parameter t will uniquely define the value of the y coordinate. Similar relationships for the x and z coordinates allow a three-dimensional curve to be uniquely determined by the single parameter t. This parameter is the distance along the original curve and this is usually approximated as the straight-line distance between points. That is:

$$\Delta t = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2} \qquad [19]$$

For the purposes of this work a surface definition using parametric cubic spline procedures provides an accurate approximation to a three-dimensional surface. The end condition used throughout this work was that of zero curvature.

The facility to define a number of bodies or separate parts of the same body independently allows complex geometries and flows to be investigated. If each body is defined relative to its own body coordinate system there has to be a means of relating the coordinate systems of all the bodies to the overall cartesian coordinate system in which the panels are defined. A set of four vectors (**S**, **P**, **O**, **A**) were used to carry out this transformation. The definition of these vectors allows great flexibility for the parametric studies of complex geometries.

Each individual body (or part body) is defined in the same manner as that of a ship hull form; as an ordered series of lines with each line containing an ordered set of three-dimensional points. For a closed lifting body such as a rudder or wing, a wake sheet will be connected to the trailing edge and it is therefore sensible to start and finish each body definition line at the trailing edge. The lines are ordered so that the normal vector to a panel always faces out into the exterior flow field.

The numerical discretisation of the body geometry into a number of quadrilateral panels requires the number of panels in the section data direction (parameter t) Nt and in the line direction (parameter s) Ns. The process of generating the Nt by Ns panels is carried out by:

1) Producing (Nt + 1) coordinates for each line of section data using a parametric cubic spline through the section data. The distribution of points within a section can either be spaced at intervals of Δt, where

$$\Delta t = \frac{|T|}{N_t} \qquad [20]$$

and T is the total parametric length of the line or where Δt is some function of t. For closed bodies the start and finish point of each line are made identical.

2) A parametric cubic spline is formed in parameter s by using the i^{th} point from each of the section data splines. Each of these new cubic splines is used to define (Ns+1) points. Repeating this for all (Nt+1) points generates the coordinates vertices for all the required panels.

The wake sheet is panelled in a similar manner. To ensure accurate matching of a body trailing edge and its wake sheet the number of section lines are the same for body and wake.

The disturbance velocity field generated by a body is superimposed on the velocity field existing in the absence of the body. For many problems this inflow velocity field is a constant velocity in the free-stream direction throughout the domain and can be directly specified. In the case of a rotating body the velocity on its surface will be the vector sum of the free-stream velocity and the body's rotational speed. That is:

$$V = U_{\infty} + r \times \omega \qquad [21]$$

where **r** is the position vector of the panel centroid from a point at the origin of the axis of rotation. The angular velocity ω vector is the scalar speed of rotation in the direction of the axis of rotation.

The modelling of the interaction between a ship rudder and propeller requires a spatially varying flow definition in the absence of a lifting-surface. So in addition to the uniform free-stream velocity and where necessary rotational velocity a spatially varying velocity distribution is needed. To facilitate modelling, a velocity field definition is used whereby the u,v and w components of velocity corresponding to velocities in the x,y and z directions are specified at a uniform spacing within a three-dimensional block. A cylindrical or cubic block can be used for the propeller and rudder inflow fields.

Theoretically, the interaction velocity field could be replaced by the location of suitably placed source/dipole panels of known strength and used directly in the calculation of influence coefficients. However, it is more convenient to specify a velocity field. If this velocity field satisfies Laplace's equation it is identical. That is if:

$$\nabla^2 \phi = 0 \qquad [22]$$

then as

$$u = -\frac{\partial \phi}{\partial x},\ v = -\frac{\partial \phi}{\partial y},\ and\ w = -\frac{\partial \phi}{\partial z} \qquad [23]$$

to satisfy Laplace's equation the interaction velocity field **Ui** must satisfy:

$$\underline{\nabla} \cdot \underline{U}_i = 0 \qquad [24]$$

or expressed as the sum of velocity differentials should everywhere equal zero:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad [25]$$

6.2 Fleximesh

The approach to geometry documented above is powerful but there are limitations imposed through the use of regular two-dimensional meshes to define bodies. For instance, at the tip of rudder it is difficult to completely close the geometry. In order to alleviate a number of problems encountered during the use of Palisupan, when the code was translated into C the opportunity was taken to rewrite the way geometry information was stored and used within the program. The code now takes advantage of the powerful data structure manipulation when writing in C.

By careful design the advantages of the existing panel generator were maintained while increasing the flexibility and to allow the use of ideas originating from the concepts of unstructured meshes and to use the output of CAD programs such as Shipshape (Wolfson Unit)

Geometry information is divided into a hierarchical structure. At the lowest level is a file containing a one-dimensional list of all the nodes used to define all bodies, sub-bodies and wake panels. The order of a node in this list will define its absolute identity number.

The second level of information will be a file of information which maps a particular panel, again identified by its absolute position within the list, to the individual nodes. For each panel the following information will be recorded:

i) The number of nodes making up the panel, generally 4 but could be 3 or 5 or greater (not implemented yet).

ii) The absolute identity numbers of all the nodes which make up the panel, listed in an anti-clockwise direction so that the panel normal points into the external flowfield.

iii) For each edge, a number which will specify either:

a) The absolute identity number of a neighbouring panel
b) A zero to indicate that its is an edge with no separation. If it is identified as a wake panel this will indicate that this is the final panel.
c) A negative number indicating a trailing edge for which a kutta condition should be satisfied. The absolute value indicating the partner panel on the other side.

iv) A number indicating the type of panel:

1: A dipole/source panel
2: A source panel of specified strength
3: A dipole panel of specified strength
4: A free-wake panel
5. A fixed-wake panel
6. A free-surface panel

The third level of information will relate individual panels to specific sub-bodies/bodies.

The fourth level of information will specify:
1 a body's absolute postion with respect to the global coordinate system (as per

POSA)

2 properties of the body e.g. a velocity, time varying velocity, angular rotation, inertial mass and moments of inertia

3 whether it is to be used as part of the interaction process e.g. if body 1 and body 2 are to be solved separately and how their relative interaction velocity fields are applied.

The final level of information will specify a potential velocity field in the global coordinate system.

7.0 Calculation of Aero/Hydrodynamic Coefficients

The numerical solution of Morino's method gives a result vector which specifies a dipole strength at the centre of each panel. As explained previously, this corresponds to the potential ϕ on the surface of the body. To obtain practical engineering information from this surface potential distribution a numerical differentiation has to be carried out. The differentiation gives the disturbance velocity tangential to the panel surface. The total velocity at the panel centroid $\mathbf{U}_t$ is the vector sum of the tangential disturbance velocity $\mathbf{U}_d$, and the normal component of the body surface $\mathbf{r} \times \omega$ and interaction field velocity $\mathbf{U}_i$.

$$U_t = U_d + \left(U_i - (U_i \cdot n)\, n \right) + \left(r \times \omega - \left((r \times \omega) \cdot n \right) n \right) \qquad [26]$$

where $\mathbf{n}$ is a unit vector normal to the panel surface.

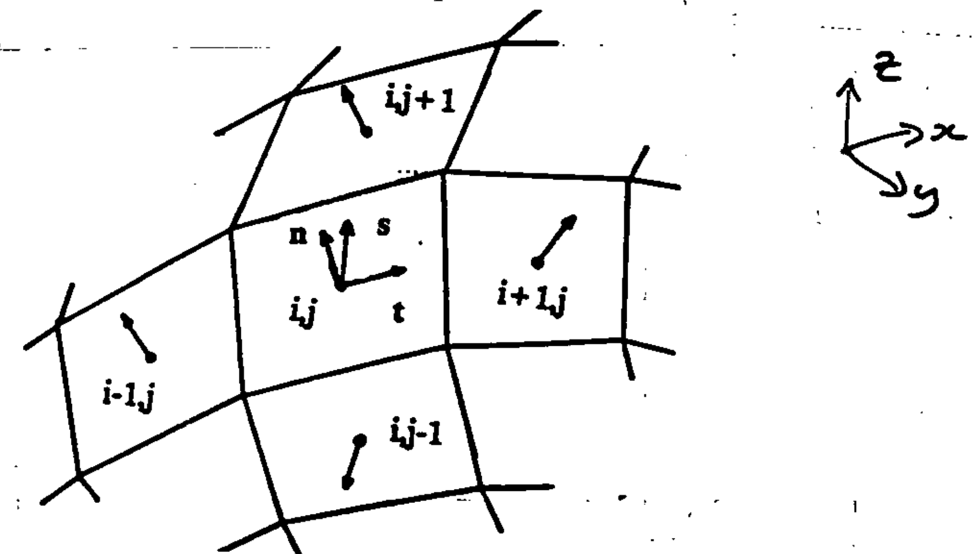

Figure 1 Detail of surface panel vectors for calculating surface velocity

There are two methods of obtaining the disturbance tangential surface velocity[15]. That is either by fitting a parametric cubic spline through the panel centroids and using the cubic polynomial constants to obtain the gradient and hence velocity, or by a finite difference approach. The spline approach requires the assemblage of information from all the panels in a particular parametric direction. On the other hand, the finite difference method only requires information about its four neighbouring panels. This is shown in Fig. 1, with the two unit vectors $\mathbf{s}$ and $\mathbf{t}$ in the local parametric directions. The velocity in the t and s directions are then obtained using a second order central difference:

$$u_t = \frac{(t_{i,j} - t_{i-1,j})(\phi_{i+1,j} - \phi_{i,j})}{(t_{i+1,j} - t_{i-1,j})(t_{i+1,j} - t_{i,j})} - \frac{(t_{i+1,j} - t_{i,j})(\phi_{i,j} - \phi_{i-1,j})}{(t_{i+1,j} - t_{i-1,j})(t_{i,j} - t_{i-1,j})} \qquad [27]$$

and

$$v_s = \frac{(s_{i,j} - s_{i,j-1})(\phi_{i,j+1} - \phi_{i,j})}{(s_{i,j+1} - s_{i,j-1})(s_{i,j+1} - s_{i,j})} - \frac{(s_{i,j+1} - s_{i,j})(\phi_{i,j} - \phi_{i,j-1})}{(s_{i,j+1} - s_{i,j-1})(s_{i,j} - s_{i,j-1})} \quad [28]$$

The finite difference was chosen because it is easier to implement and for panels which closely follow the curved surface of comparable accuracy to that of the parametric spline method.

Having determined the surface velocity in the parametric coordinate system a transformation has to be carried out to give the surface velocity components in the overall coordinate system. Unit vector **s** and **t** are not necessarily orthogonal and therefore the velocities are first transformed into an orthogonal system with one direction normal to the panel. The u,v and w components can then be found. The combined expression as given by Lee[16] becomes:

$$\underline{U}_d = \frac{\frac{d\phi}{dt}\left(\mathrm{t} - (\mathrm{s.t})\,\mathrm{s}\right) + \frac{d\phi}{ds}\left(\mathrm{s} - (\mathrm{s.t})\,\mathrm{t}\right)}{||\,\mathrm{s} \times \mathrm{t}\,||^2} \quad [29]$$

Knowing the disturbance velocity $\mathbf{U}_d$ and hence total velocity $\mathbf{U}_t$ allows the local non-dimensional pressure coefficient Cp to be found.

$$Cp = 1 - \frac{U_t^2}{U_\infty^2} \quad [30]$$

The integration of the pressure distribution over the N panels defining the body surface allows the total potential pressure force **F** on a body to be evaluated as a vector sum, where A_i is the area of the i^{th} panel and $\mathbf{n}_i$ the direction of its unit surface normal, and N the number of panels on the body.

$$\mathrm{F} = \tfrac{1}{2}\rho U_\infty^2 \sum_{i=1}^{N} C_{Pi} \cdot A_i \cdot \mathrm{n}_i \quad [31]$$

The calculation of the pressure components of the non-dimensional body force and moment coefficients requires a further transformation into the correct body coordinate system. For example, as shown in Fig. 1, for a ship rudder at incidence with the x direction in the free-stream direction and z vertical the lift is the **j** component of **F**. That is:

$$C_L = \frac{\mathrm{F.j}}{\frac{1}{2}\rho U_\infty^2 sc} \quad [32]$$

where s and c are respectively the rudder span and mean-chord. The pressure component of Drag is correspondingly:

$$C_D = \frac{\text{F . i}}{\frac{1}{2}\rho U_\infty^2 sc} \qquad [33]$$

An estimate of the viscous skin friction force acting on a lifting-surface can be found by using the panel surface velocity and distance from the leading edge to estimate the skin friction coefficient C_f. This gives a viscous force contribution equal to:

$$\mathrm{F}_{visc} = \frac{1}{2}\rho\sum_{i=1}^{N} C_f \; A_i \left(\mathrm{V}_T \;.\; \mathrm{V}_T \right)\mathrm{V} \qquad [34]$$

where **v** is a unit vector in the local flow direction. The skin friction coefficient is calculated in terms of local Reynolds number:

$$Rn = \frac{|\,\mathrm{U}_\infty\,|\, s}{\nu} \qquad [35]$$

where s is the distance to the leading edge. The expressions used for C_f are from Schlicting[18]:

$$Rn < 3x10^5 \quad C_f = 0.664\,Rn^{-0.5}$$
$$3x10^5 \le Rn < 1x10^7 \quad C_f = 0.074\,Rn^{-0.2} - 1050\,Rn^{-1} \qquad [36]$$

Combining the viscous and pressure contributions gives the total force F_T acting on the body as:

$$\mathrm{F}_T = \mathrm{F} + \mathrm{F}_{visc} \qquad [37]$$

It should be noted that this neglects the change in pressure force due to viscous effects. Similar expressions are derived to give the total moment acting about the body pivot **P**.

CONVERTING TO DIMENSIONAL FORCES/MOMENTS

The forces/moments are non-dimensionalised with respect to the dynamic pressure and a fixed area of 0.667 m^2 and for the moments a fixed length of 0.667 m. The viscous force contribution is based on the use of **air** and hence the Reynolds number and skin friction coefficients use the density and viscosity of air at standard conditions. To ensure that the frictional force reflects different conditions/fluids eg. water the reference velocity should be scaled appropriately. The equivalent velocity in air for a hydrodynamic problem is found by equating Reynolds number :

$$V_{air} = V_{water}\left(\frac{L_{water}}{L_{air}}\right)\left(\frac{\nu_{air}}{\nu_{water}}\right) = 12.842\, V_{water} \qquad [38]$$

8.0 How to Use Palisupan

8.1 On Unix Workstations

Create a directory in which to mount the executable code:

mkdir panels <rtn> {creates a directory panels}

Then transfer the executable code *Malisupan* using the filemanager or FTP. Remember as it is executable code it has to be transferred as BINARY. The permissions of the executable code will also need to be changed using the following Unix command

chmod 777 Malisupan <rtn>

Ensure that the following files exist in the same directory as *Malisupan* :

GeometryFileName.cmd The command file (see section 8.5)

and

GeometryFileName.pan or *GeometryFileName*.uns

where the suffix .pan is used for original structured geometry files and .uns for fleximesh geometry files.

The program can then be run as follows:

%: Malisupan<rtn>
%: *GeometryFileName*.cmd<rtn>

The *GeometryFileName*.log file records all the output generated by the code as controlled by the command file. Note: a new name should be used if the previous log file is to be kept.

8.2 Geometry File Creation

The definition of the geometry files can be done in a number of ways. Manually through the use of a text editor either by creation from scratch or by modifying an existing file or automatically through the use of specially written geometry creation program. A number of these exist, for example a code is available to create propeller geometries from a standard table of propeller offsets. The format of the structured geometry input is described in detail in Appendix A and that of the new fleximesh in Appendix B. The program does not necessarily crash immediately if there is a mistake within the input file. However, this is often the source of latter problems and the geometry input file should be the first point of investigation.

8.3 Command File Creation

The command file has a straightforward format which allows control of the program and can save effort by allowing multiple runs of the same geometry under different flow conditions. It also allows multiple body interaction problems to be studied. The output from the program is controlled using five switches to determine whether the log file records total forces, panel centre pressures and potential, field velocities at a series of specified nodes, panel geometries, and body parameters.

The command file is a text (ascii) file and its format is as follows with individual items separated by at least one space:

(I=integer, R = real, S = string)

Line 1: I_NoGeom I_NoVariations I_MinNoIt I_MaxNoIt R_MinLim R_MaxLim

{ repeat for i = 1 to I_NoGeom }

Line i.2:	R_CpMax R_CpMin I_NoBlocks I_DSex I_Wex I_Ftype I_Vcode
Line i.3:	I_RecordF I_RecordCp I_RecordV I_RecordParam I_RecordGeom I_RecordAVS
Line i.4:	S_BGfname
Line i.5:	S_Dname
Line i.6:	S_Sname
Line i.7:	S_Wname
Line i.8:	S_Vname
Line i.9:	S_RootName
Line i.10:	I_Fcomp I_Rotation I_NoImage I_MaxF I_MinF I_LastF I_Lcrit
Line i.11:	R_axis.x R_axis.y R_axis.z R_origin.x R_origin.y R_origin.z
Line i.12:	I_NoChanges

{repeat for j = 1 to I_NoChanges}

Line i.j.13: I_variant I_BNo I_ParamNo I_Comp R_value

Definition of Terms

Line 1: OVERALL COMMAND LINE

I_NoGeom	Defines the number of geometries used to solve interaction problems (see later). For most problems a geometry will be made up, if necessary, of a number of bodies defined within one geometry file.
I_NoVariations	To allow parametric variations, for instance a range of incidence angles, the program can automatically carry out a number of variations of easily changed parameters. The value of this parameter is equal to the number of variations carried out, eg. one incidence would be 1, two incidence would be 2 etc.
I_MinNoIt	The iterative solution procedure for the surface panel method can be forced to carry out at least I_MinNoIt iteration cycles. Normally, it is set to 1.

I_MaxNoIt	A poorly defined problem may converge/diverge very slowly and to ensure that a problem can finish within a reasonable time a maximum number of iteration cycles has to be defined. The user may wish to alter this parameter for a particular type of problem.
R_MinLim	The block iterative matrix solver is forced to converge to a certain limit as set by this parameter. Normally this is set to no higher than 0.0001 but the user may wish to investigate the influence of this parameter on the solution.
R_MaxLim	If the solution of the block iterative solver is diverging this parameter will cut-off the calculation at a given level and is usually set at 50.0. However, it is worth noting that for some geometries this value may be exceeded and yet the solution will eventually converge. Divergent solutions are either due to poorly defined geometries or the incorrect partitioning of the solution matrix through the incorrect choice of the number of blocks.

{ repeat for i = 1 to I_NoGeom }

Line i.2: KUTTA CONDITION/MATRIX FILES/Velocity Code

R_CpMax	This cuts-off the excution of the code when the iterative kutta condition is diverging at the set level.
R_CpMin	This sets the convergence of the maximum trailing edge pressure difference. Too small a value will result in a large number of iteration cycles and too high a value will give a poor prediction of pressure distribution and hence force.
I_NoBlocks	This defines the number of equal sized blocks that the influence coefficient matrix is partitioned into. This can be a crucial parameter both for the number of iteration cycles and hence speed of convergence and for ensuring that convergence actually occurs. For single body problems the no of blocks should be set equal to the number of wake strips.
I_DSex	A boolean switch which determines whether the dipole and source influence coefficient matrices are calculated (0) or read from previously stored files(1). Care should be taken that the influence coefficient files match the specific problem.
I_Wex	A boolean switch which determines whether the wake influence coefficient matrix is calculated (0) or read from previously stored files(1). Care should be taken that the influence coefficient file matches the specific problem.
I_Ftype	A boolean switch which indicates the geometry file format. A value of 0 indicates the original Palisupan file format and 1 teh fleximesh format.
I_Vcode	The value of this integer determines the field velocity recorded using the I_RecordV parameter. 1= dipole panel velocity influence, 2=source panel velocity influence, 3=wake panel velocity influence, 4=dipole+source+wake+impeller velocity influence, 5=impeller velocity, 6=body velocity, 7=field velocity, 8=total velocity.

Line i.3: RECORDING PARAMETERS

All the integers on this line are Boolean switches. A value of 1 indicates that the parameter will be recorded in the LOG file and 0 that it is not recorded.

I_RecordF	The three components of force and moment for each separate body and geometry are recorded. These force/moment components are defined in the global cartesian coordinate system [x,y,z] and are presented in non-dimensional form. The forces are non-dimensionalised with respect to the reference inflow velocity and an area of 0.667 m^2 and the moments use an additional lever length of 0.667 m.
I_RecordCp	This records for all body and wake panels making up the bodies of a given geometry the non-dimensional pressure coefficient Cp and velocity at panel centre along with the cartesian coordinates of the panel centroid.
I_RecordV	This records the velocity at field points within the flow as defined by cartesian coordinates as stored in S_Vname (Line i.8). Note to use this a file, S_Vname must exist.
I_RecordParam	The relevant set of vectors defining each individual body's orientation are recorded. This is a useful check to ensure the desired parameter variations are as expected.
I_RecordGeom	The cartesian coordinates of the nodes which define all the panels are recorded. This is useful for understanding the position and distribution of panels used.
I_RecordAVS	This parameter produces a separate file for each geometry suitable for use by the AVS visualisation software. The information for each body is stored in a file with S_RootName prefix and suffix made up of the body number followed by AVS.

Line i.4: FILENAMES

S_BGfname The file name of the geometry input file (include directories as appropriate)

Line i.5:

S_Dname The file name suffix for the dipole matrix file eg. S_Dname.dij. BEWARE, this file becomes very large for large numbers of panels.

Line i.6:

S_Sname The file name suffix for the source matrix file eg. S_Sname.sij. BEWARE, this file becomes very large for large numbers of panels.

Line i.7:

S_Wname The file name suffix for the wake matrix file eg. S_Wname.wik BEWARE, this file becomes very large for large numbers of panels.

Line i.8:

S_Vname The file name for the cartesian coordinates at which velocity field information is required. The first line states the number of points and each subsequent line gives the x, y, and z ordinates for each point in the global coordinate system.

Line i.9:

S_RootName The root file name specifies the suffix for the .LOG file.

Line i.10: INTERACTION VELOCITY FIELD DATA

I_Fcomp The component of force which is used for checking interaction problem convergence. 0 = Fx, 1=Fy, 2=Fz, 3=Mx, 4=My, 5=Mz.
I_Rotation If the body is rotating, eg. propeller this is set to zero
I_NoImage For a rotating body, the number of images.
I_MaxF The divergence limit on force convergence
I_MinF The convergence limit on interaction force component
I_LastF An initial value for testing percentage change in force
I_Lcrit A length used to determine the number of velocity points for a rotating body problem

Line i.11: INTERACTION AXIS AND ORIGIN

R_axis.x, R_axis.y, R_axis.z The unit vector defining the direction of rotation
R_origin.x, R_origin.y, R_origin.z The unit vector defining the point about which the velocity field is generated.

Line i.12:

I_NoChanges The total sum of the number of lines within the parameter variation list. The reason this is not necessarily identical to the I_NoVariations is that for each variation a number of bodies and body parameters can be changed

Line i.j.13: PARAMETER VARIATIONS

I_variant The change is associated with a particular variation, starting from 0.
I_BNo The body for which the parameter change is associated, again starting from zero.
I_ParamNo The parameter code to be changed. 0=offset, 1= scale, 2=pivot,

	3=angle.
I_Comp	The force component to be changed, 0=x, 1=y, 2=z.
R_value	The value to be used for variation.

For example, to set body zero to an angle of 30 degrees about the z axis. Th efollowing would be used.

0 0 3 2 30.0

Care should be taken if rotating a body about more than one axis at a time as the process is not commutative.

NOTE

Although containing a large number of terms it is often the case that a simple modification to an existing command file allows a new command file to be rapidly created.

8.4 Post-processing Data

The six different recording parameters in the command file allow different information to be recorded for each of the geometries. All the information requested is recorded in a single log file. Data is recorded as text. This can be extracted using standard text editors or imported directly into spreadsheet package such as Excel or again a specific program can be written to analyse the data. The level of analysis required will dictate which recording parameters are used.

8.5 Multiple Geometry Problems

It is possible to break down a problem rather than as a series of individual bodies making a single geometry as a series of geometry files. In this case an overall iteration takes place where the velocity influence of one body is determined and is used as an input to the next geometry. This can be carried out for a number of geometry files. The process was developed specifically to solve rudder-propeller interaction (Ref.[2]) and has been generalised for n bodies.

9.0 Validation

A mathematical model of a physical process generally involves a degree of approximation. In using such a model it is necessary to appreciate the confidence with which the model can be used. In the same way in which there is always error (or more correctly a degree of uncertainty) in the acquisition of experimental data, numerical modelling gives rise to uncertainty in the answer obtained. The process of validation attempts to quantify these uncertainties.

The precise definition as to what constitutes a validated CFD code is the subject of debate at the present time. The process of code validation can be seen as a series of stages.

1) **Verification** of the code implementation against the underlying mathematical formulation. This is to ensure the code is free of error due to mistakes in expressing the mathematics in the particular computer language used. ideally the comparison should be made against an analytic solution although often the comparison can only be made with other numerical codes.

2) Investigation of the **independence** of the solution from numerical parameters. The most common form of dependence is on the density of the grid of points at which the governing equations are solved. Normally, the number of grid points (or panels or whatever is used to discretise the governing pde's) is increased until the solution does not change. For iterative techniques which use a convergence criterion the dependence of solution on its value has also to be investigated.

3) **Comparison** of numerical and experimental data. This is the most tendentious area of code validation. as the majority of fluid dynamic codes are an approximation to the actual physics of the flow there will be differences between the experimental and numerical results. Experimental data should have a specified accuracy. This should then allow the difference between experiment and theory to be quantified. However, in many codes some degree of empiricism is used to adjust the numerical model to fit specific experimental data. The extent to which such an empirically adjusted model can be said to be valid for cases run at different conditions requires careful consideration.

Historically, experimental data has often been used to improve the correspondence between theory and experiment to provide a design tool. Such an approach will usually restrict the range of geometries/conditions for which the model can be used. This can be dangerous if these restrictions are not appreciated/understood by an end-user who could use the code for a completely different geometry and then base design decisions on what is a fundamentally flawed analysis. It is my belief that empirical modifications (the ubiquitous fiddle factors) should be avoided wherever possible within the CFD codes themselves to avoid this danger. This does not mean that such experimental evidence should not be used but that it should be included as part of the analysis process and not directly within the code. This is the approach adopted within the surface panel code where, for instance, the user can include estimation of such quantities as skin friction using empirical formulae. Or, at a more sophisticated level introduce panels which follow the separation boundary and hence produce a more realistic model (Ref.[3]).

10.0 User Exercise - Free -stream Rudder

10.1 Free-stream Rudder and Wake Definition

The aim of this exercise is to produce a geometry input file for an all-movable rudder and then to use it to carry out a series of validation procedures. These procedures are indicative of the controlled development of a suitable surface panel model from which reliable data can be obtained.

The test geometry is based on a constant NACA0020 section all-movable, rectangular rudder, with a 1 m span and 0.667 m chord, no sweep and with the rudder stock set at 30% of the chord from the leading edge. Appendix A contains all the information necessary to produce a text file in the Palisupan Original Format and a brief description of each individual component of the file.

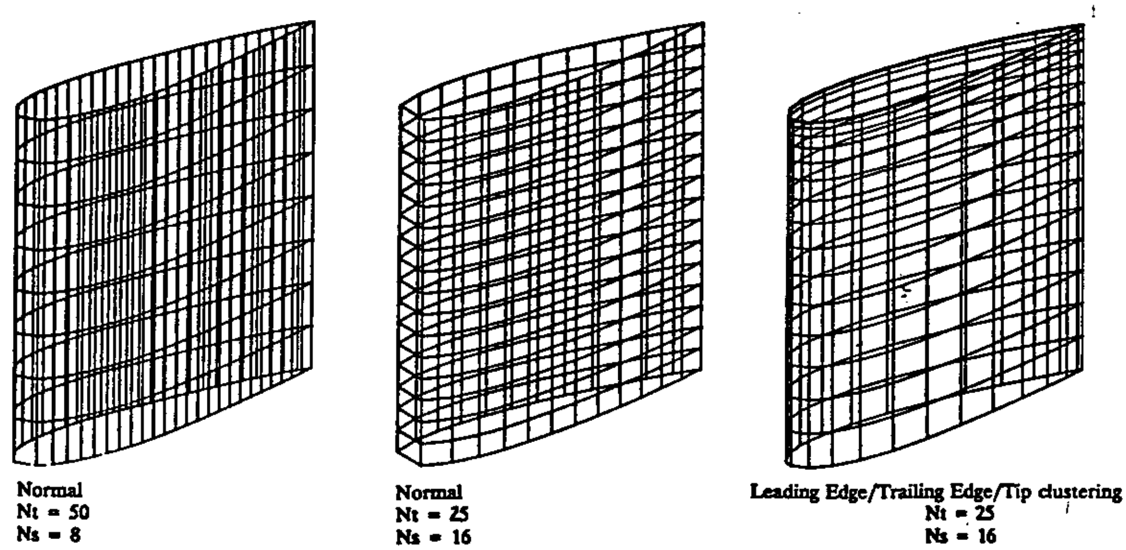

Figure 2 Three possible rudder panel distributions

Figure 2 shows three possible rudder panel distributions. It should be noted that the rudder is defined with a reflection plane at the rudder root thus doubling the effective aspect ratio and corresponding to the flow over the rudder adjacent to a flat plate.

The first step is to create a text file containing the information given in Appendix A. As this file is created it is important to be able to identify the various elements which allow control over the final developed form of the rudder surface. Note, the program is unforgiving and the file has to be accurate with the relevant information at the correct location. A common error is to enter too few or too many coordinates defining a curve in comparison to the number of points specified. The file should be saved with the designation *.pan* and a suitable name in this instance would be *rudder.pan*. Any text editor (wordprocessing or spreadsheet package) which allows standard ASCII text files to be created can be used to generate the file. For more complex geometries it may be time effective to write a specific computer program to automatically generate an input file based on user inputs.

The rudder is a lifting surface and needs a trailing wake sheet specified for each section. In this case a wake is defined which trails back in the direction of the rudder chord axis. As the wake sheet is defined using a spline more complex shapes can be produced but for the purpose of this exercise this is not necessary. For non-rotating bodies the program uses two zones for defining the wake sheet. The spline shape defined by the geometry input file is panelled with Nw-1 panels in the chordwise direction and Ns-1 panels in the spanwise direction. At the end of the wake sheet the direction of the last panel is used to fix the direction of a semi-infinite wake sheet trailing to infinity. The numbers of panels, Nw-1, should be chosen to give approximately the same size of panels in the wake as on the body.

The second stage in the process is the construction of a command file. A suitable file would be as follows:

```
1[i]  1[ii]  1  100    0.00001      50.0
30.0  0.01[iii]  4[iv]  0 0  0  4
1[v] 0 0 0 0 1[vi]
rudder.pan[vii]
rudder.dij
rudder.sij
rudder.wik
rudder.nde
rudder[viii]
1 0 1 0 100.0 0.1 1.0 0.05
0.0 0.0 0.0 1.0 0.0 0.0
1[ix]
0 0 3 2 0.0[x]
```

This file should also be created as a text file and a suitable name is *rudder.cmd*. The important features to note about this command file are as follows:

(i) It is a single geometry problem
(ii) The geometry file is to be run for only one variation
(iii) The minimum Cp convergence criterion is set at 0.01
(iv) The number of blocks is set at 4. This should be set equal to the number of panel strips (Ns-1) in the spanwise direction
(v) This ensures that a LOG file is generated containing the force values
(vi) This ensures a visualisation file in the AVS format is produced.
(vii) This is the filename of the geometry file for input (with directory extensions if appropriate.
(viii) This is the header name for the output files eg. rudder.LOG or rudder.0AVS.
(ix) This shows only one change in input properties.
(x) This indicates that parameter 3 (angle), component 2 (z axis) is set to 0.0°

Once both files have been defined and are in position the program can be run using the *rudder.cmd* file. The program will work if the files have been correctly defined otherwise it is a case of patiently checking for errors.

10.2 Effect of Rudder Incidence

There are two methods of achieving a geometric angle of incidence between the rudder and the onset flow. These are to:

1) Alter the direction of the velocity field vector from straight along the x axis V = 1.0, 0.0, 0.0 to for example a 20° angle of incidence, V = 0.9397, 0.342, 0.0. However, care has to be taken in that forces are always resolved about the global x, y and z axis and so obtain C_L and C_D the forces have to be rotated by 20° as well.

2) A more effective method for investigating multiple rudder incidence and deriving a performance chart is to specify a number of incidence as changes. For example, the command file should be modified as follows to give results at -5.0°, 0.0°, 5.0°, 10.0°, and 15.0° changes are shown in *italics*

```
1  5  1  100    0.00001     50.0
30.0  0.01  4  0 0  0  4
1 0 0 0 0 1
rudder.pan
rudder.dij
rudder.sij
rudder.wik
rudder.nde
rudder
1 0 1 0 100.0 0.1 1.0 0.05
0.0 0.0 0.0 1.0 0.0 0.0
5
0 0 3 2  -5.0
1 0 3 2  0.0
2 0 3 2  5.0
3 0 3 2  10.0
4 0 3 2  15.0
```

In this case the number of changes equals the number of variations. For geometries with more than one body, for each variation there can be at least one change associated with each body. These multiple variations work by assuming that the relative influence of each body on all others remains the same. That is, the dipole, source and wake influence matrix are only calculated for the first variation and are then assumed constant for all remaining variations.

When the above command file is run the *rudder.LOG* file should contain the pressure force, estimated viscous force and total force (and associated moments) for all five angles. This data can be used to generate performance data. For example C_L, or C_D versus rudder incidence. An instructive plot is that of C_D versus C_L^2. If this plot is carried out for the pressure force component alone it indicates the numerical error associated with the drag calculation. A potential flow solution will have no induced drag for zero lift and the curve should therefore go through zero.

The command file only generates one AVS file per run and so for each rudder incidence the new solution file overwrites the old one. It is instructive to visualise the rudder flow using AVS. Many problems can be isolated through visualisation. A common error is to define a geometry in which the panel normal vectors face inwards. This can be simply spotted in AVS as the panel colours will appear shaded rather than bright (and the iterative kutta condition will converge very slowly, if at all).

Another important set of validation data is the comparison of surface pressure Cp (and associated velocity) between the numerical solution and experiment. This data can be obtained by switching the I_RecordCp variable to 1. The tabulated data which occurs in the LOG file can then be imported into a spreadsheet for further analysis and presentation.

Important

Currently, the forces and moments output by the program are non-dimensionalised with respect to the reference velocity, an area of 0.667m^2, and a lever arm of 0.667 m. In this case the rudder does have these properties and so C_Y corresponds directly to C_L and likewise C_X to C_D. However, for bodies with different projected areas/lever arms the results should be scaled appropriately.

10.3 Investigation of Minimum Cp Criterion

At this stage the user should be familiar with running the program and obtaining forces, pressures for a given geometry and flow incidence. However, it is essential that the influence of the various numerical parameters on the results are understood and quantified.

The first stage of this process is that for a lifting body (eg. rudder at incidence) the influence of the iterative kutta condition on the forces/pressures is known. A straightforward solution would be to make the minimum Cp value as close as possible to zero. The obvious drawback is that thousands of iterations would be required to obtain a converged solution. Some form of compromise is needed and a systematic approach should be used to obtain the maximum value for the difference in trailing edge Cp for which no further significant change in force/pressures will occur. A straightforward exercise to appreciate this effect would be to run the program for minimum Cp values of say 0.1, 0.01, 0.001 and record the force values and the number of iterations required.

10.4 Investigation of Panel Size and Panel Aspect Ratio

The discretisation of the actual (continuous) rudder surface into a finite number of quadrilateral panels has associated with it a loss of accuracy. Again, this discretisation error should be quantified. With this program this is a relatively straightforward process. In the case of the rudder, and for most lifting surfaces, there are two parameters Nt and Ns which between them control the total number of panels and the relative number in the spanwise and chordwise directions. The two physical parameters which control the error are the surface velocity gradients and the local surface curvature and the two guiding principles for determining panel distribution should be that panels are concentrated in areas of high curvature or high velocity gradient.

The rudder provides a good geometry for investigating these effects. It has zero curvature in the spanwise direction, high curvature and velocity gradient close to the leading edge. However, it has a low aspect ratio and a square tip so there will be three-dimensional flow features which increase in magnitude for higher incidence and close to the rudder tip. The next section describes how the panel generator allows relative variations in panel size for both the chordwise and spanwise directions. The initial problem is in determining the relative number of panels in the two directions and in the total number of panels. A three stage process is used to optimise these combinations:

i) For a constant number of panels in the chordwise direction eg. Nt is constant, the number of panels in the spanwise direction should be varied. Typical values would be Nt = 26 (25 panels) and Ns = 5, 9, 13, 17 etc. Please note that as Ns is changed the number of blocks used in the matrix solution should be correspondingly changed eg in this case they would be set at 4, 8, 12, 16. The force component results should then be plotted against the total number of panels used (Nt-1)*(Ns-1). There should only be a small variation in force for the rudder geometry.

ii) For a constant number of panels in the spanwise direction eg. Ns is constant the number of panels in the chordwise direction should be varied. Typical values should be Ns =9 (8 panels and 8 blocks) and Ns = 26, 36, 46, 56 etc. The force component results should then be plotted against the total number of panels used (Nt-1)*(Ns-1). There should be a much larger variation in force for the rudder geometry.

iii) From the two previous variation studies it should be possible to identify an optimum ratio of Nt-1 to Ns-1. A suitable combination for this rudder is Nt=26 and Ns=9. Maintaining the same aspect ratio the total number of panels should now be varied. Likely combinations are:

Nt	Ns
14	5
26	9
39	13
51	17
etc.	

Again the variation of force component with total number of panels should be plotted. It is likely that even at the maximum possible number of panels the line will still not have converged. However, the variation with total number will at least allow an estimate of the difference from the fully converged solution.

10.5 Influence of Panel Distribution

The panel generator allows the relative size of a panel within a given direction to be varied. Again, this will have an influence on the numerical solution. Possible panel distributions in the chordwise directions are 0, 2, 3 and 4 (symmetrical distributions are needed). In the spanwise direction possible distributions are 0 or 1 (others such as 2, 5, 6 or 7 could be used but do not match the flow expected). For a given total number of panels and optimum ratio of Nt-1 to Ns-1 the different combinations of distributions should be attempted. In general, the optimum distribution will be the one for which C_L is a minimum and C_D a maximum.

10.6 Influence of Matrix Block Size

The dipole influence coefficient matrix is (normally) diagonally dominant, eg. the leading diagonal is the largest value for any given row or column. This ensures that an iterative Jacobi scheme, where the leading diagonal element is used to iteratively estimate the solution, should converge. However, the problem is that it will take a large number of iteration cycles to converge and this coupled with the iterative kutta condition will result in an enormous computational effort for a given geometrical set-up. In some cases this may be the only means to obtain a solution and in this case the I_NoBlocks value should be set equal to the total number of panels for a given geometry input file, eg. sum for all bodies of (Nt-1)*(Ns-1).

For single body problems or multiple body problems for which the interaction effects between bodies are not large then a much more rapid block-Jacobi approach can be used. The definition of a lifting surface into chordwise strips of panels results in a banded matrix structure in which the inverse of a series of small sub-matrix blocks can be used in the iterative process. The most effective sub-matrix size is chosen to be equal to the number of panels in a given chordwise panel strip eg. if Nt = 26 then the number of panels per block equals 25 and the total number of blocks for a single body problem is Ns - 1. For multiple body problems a constant block size still has to be used for the matrix. So either all bodies have to be defined using the same number of panels in a given chordwise strip or the number of panels in a block size has to be a given multiple of the minimum number of panels in a chordwise strip.

A common problem is the definition of the wrong number of blocks. In this case the banded structure is not correctly identified and the iterative solution will usually diverge. Note that the value of R_MaxLim controls the value at which the solution procedure is stopped if the value is diverging. Likewise, R_MinLim controls the level at which the matrix solution is assumed to have converged. This is normally set at 0.00001.

For multiple body problems in which the individual bodies are in close proximity it is likely that problems will arise with large individual dipole influence coefficients occurring outside the banded structure. If this is the case, the block Jacobi procedure will not work and as the single element Jacobi is very time consuming the problem should be tackled as an interaction process. In this, each body is defined as a separate geometry input file and the relative influence of each is accounted for through their relative influence on each body's inflow velocity field.

10.7 Likely Problems

The main problems which occur are with poorly defined geometry input files. As a first stage these should be checked thoroughly.

(i) If the program halts while reading in the geometry file this usually implies that a number is missing or is in the wrong place.

(ii) If the program passes through to the matrix iteration stage and then diverges this usually implies the wrong number of blocks have been specified.

(iii) If the program when in the trailing edge pressure condition the ΔCp value diverges or stays at a high value and does not reduce this usually implies that the spline created panel surface has problems with possible panel cross-over. A good check at this stage is to use the create AVS file option and read the file into a geometry net such as given in Appendix E. Note: in order to create this file it will be necessary to set the Min Cp condition sufficiently high that the program actually does terminate. Observation of the individual panels should indicate potential problems in surface definition. If there are "wobbles" in the spline curve these can usually be removed through the judicious use of extra points or section curves. As a cubic spline curve is used straight edges either side of a corner can be ensured through the placing of extra points close to the corner as shown in Figure 3. Another common error to be aware of is that of the normal to the individual body panels pointing inwards rather than outwards into the flow. This problem is removed by reversing the direction of definition of for instance the sections or the order of the sections.

10.8 Comparison with Free-stream Data

A set of wind tunnel experimental data are available for this rudder geometry. The use of this data shows the typical kinds of comparison which are possible with a surface panel code.

(i) Total Forces

A strain gauge dynamometer was used to measure five components of force/moment. Table 1 gives these values against rudder incidence for a freestream wind speed of 10 m/s.

(ii) Sectional Forces

Two hundred surface pressure tappings were distributed over the surface of the rudder. Integration of these around a chord for a given span allow the local sectional lift force to be calculated. Table 2 gives span wise integrated data for a rudder incidence of 9.6° and 19.6°.

(iii) Surface Pressures

Table 3 gives the value of the pressure tap locations and the corresponding Cp value acquired.

(iv) Velocity Field

Although no velocity field information is available for this rudder the panel code does allow the user to specify a number of field points at which velocity values are required. This can be simply done by switching the option on using I_RecordV. In order for this to work a file defined as S_Vname must exist and contain the requisite information. The component of velocity returned in the LOG file can be adjusted using I_Vcode.

11.0 Assignment: Keel-Bulb Interaction

11.1 Aims and Objectives

The aim of the exercise is to investigate, using a surface panel code, the hydrodynamic performance of a representative yacht keel-bulb and to thereby suggest methods to improve its performance. The specific objectives are to:

i) Develop a geometry input file in Palisupan input format of the specified keel-bulb geometry.
ii) Discover the most appropriate method of panel distribution to use no more than 800 body panels in total.
iii) Validate the numerical prediction against the experimental data provided.
iv) Investigate possible changes in keel-bulb geometry to enhance sideforce production while minimising drag (skin friction and induced). The design constraints are that the bulb volume remains fixed as does the maximum depth of the keel.

11.2 Problem Definition

Bulb keels are used to provide the maximum righting moment and hence sufficient sail carrying power (stability) with minimum displacement. Bulb keels are currently legal under the International Offshore Rules (IOR), whereas winged keels are not. The two specific hydrodynamic design problems are the attachment of the ballast mass to the keel and the attachment of the keel-bulb combination to the hull. This investigation is concerned only with the effect of the keel and bulb combination and not the influence of the hull. To this end it can be assumed that the hull can be replaced by a flat plate (reflection plane) and that there is no angle of heel.

The keel considered is for a yacht with the following specification:

Sail Area :	95 m^2
Ballast :	4145 kg
Displacement:	7650 kg
Total Draught :	2.66 m
Keel Draught:	2.16 m

The function of a sailing yacht keel is to control and to balance the forces and moments generated by the sails. As described in Ref.[20], considering a displacement keel boat going to windward, the keel is designed so that:

i) The heeling force due to the sails must equal the side force developed by the under body (hull, keel and rudder).
ii) The thrust developed by the sails must equal the drag on the under body.
iii) The heeling moment due to the sails must be counteracted by the righting

moment developed by the hull and keel.

Thus the keel must:

i) help the under body develop adequate sideforce at small angles of leeway with minimum drag.

ii) get the ballast as low as possible in the boat in order to maximise the righting moment for a given displacement.

Assuming that boat speed is the primary objective the design of keel and bulb should be adjusted such that a maximum side force/resistance ratio is achieved in the range of expected boat speeds and side force. The efficiency of the keel lies partially in its ability to produce the necessary lift or resistance to broadside drift. The chief factors governing this are the aspect ratio mainly governed by draught and the profile of the of the bulb for end plate effect. Considering racing yachts, the draught is fixed by regulations and therefore improving the efficiency of the keel implies designing the profile of the bulb with the best lift/drag ratio for a given required side force.

11.3 Keel-Bulb Geometry Definition

The initial keel geometry consists of two parts as shown Figure 4:

i) a fin part whose section is a NACA 63 A015, with a constant chord of 400 mm, draught = 660 mm and sweep angle = 7°

ii) a bulb part whose profile can be described as flat bottomed bell shaped, draught = 224 mm and overall length for the bulb of 808 mm.

This keel-bulb combination was tested in the 2.1 m x 1.5 m closed return wind tunnel, Ref.[5], and is a scale model of the keel-bulb used for the specified yacht design parameters. Figure 3 shows a representative equivalent keel (without ballast) and the actual keel-bulb combination. The performance of the combination at a wind speed of 40 m/s, as lift C_L and drag C_D plots, is shown in Figs. 5 and 6 (Figs. 37 and 38 of Ref. [5]). The non-dimensional area used is based on the equivalent fin, i.e. one with the same span of 864 mm and chord of 400 mm. The geometry input file for this combination is given as Appendix D. In the file, the combination is defined as two bodies, with the fin first followed by the bulb. The bulb is defined as a series of sections with the deepest first. The model was tested in an inverted position in the wind tunnel and this is the same in the numerical model.

11.4 Calculation of Keel- Bulb Intersection

A mentioned previously, it is possible to define a single geometry either as a single body or as a number of bodies which join together to make up the complete geometry. The keel-bulb is probably best defined as two separate bodies as there is usually a discontinuity in span wise surface gradient at the intersection of bulb and fin. For different bulb definitions to that used, it may not be possible to use a planar section for the intersection of bulb and fin. As the section is defined in terms of a three-dimensional cubic spline once the line of intersection of bulb and fin has been found this line should be used as a starting/finishing section on both bulb and fin. For a body of revolution this line of intersection can be found by comparing the fin section width at a given chord wise position with the height on the bulb for the same width and chord wise position. A more complex bulb shape, such as a beaver tail may need an iterative process. It is worth noting that in order for the bulb to enhance lift by acting as an endplate circulation has to be shed from the bulb. A sharp trailing edge helps control where this circulation is shed and gives more predictable performance.

11.5 Suggested Design Modifications

A number of sensible design modifications are possible. However, the following parameters have to be kept constant:

i) the righting moment, which means that the volume and the vertical centre of gravity have either to be kept constant independently or compensate one another. If the vertical centre of gravity distance (V.C.G.) is increased by stretching the bulb the, then the volume must be decreased so that the product of the volume x V.C.G. remains constant;

V.C.G. = 977 mm
Bulb Volume = 0.008942 m^3

ii) the overall draught of the keel;

Draught = 884 mm

Any shift in longitudinal centre of gravity must be kept relatively small. However, this parameter is not fully constrained as this shift may be overcome by redistributing other vessel components.

Two types of modification are possible: changes which involve minor modification to such things as the sweep or aspect ratio of the fin, stretching or fattening the bulb; or more major changes such as a different form of bulb or fin.

11.6 Contents of Report

A technical report should be presented which details the development of a suitable numerical model which has been validated against the available experimental data. Proposed design changes should be justified and the changes in hydrodynamic performance obtained presented. The likely influence of the neglected flow physics should also be estimated. The actual geometry input files used should be included as appendices. In conclusion, a recommendation for the best design investigated should be made. This exercise is intended to be a realistic design and as such only a limited amount of time is available and computing costs should be likewise minimised so the number of design changes by necessity should be small.

12.0 Future Developments

The development of the Palisupan surface panel software is on-going. At present, investigations are underway into the following areas:

i) Solution of unsteady flow, multiple body motions

ii) A more effective method for incorporating viscous flow through the incorporation of a two-dimensional boundary layer calculation which is used to alter iteratively the body source strengths.

iii) The use of an adaptive free-surface panel boundary condition to allow calculation of wave making resistance.

iv) The development of a multiple processor/workstation implementation of the code using the MPI (Message Passing Interface) procedures.

As time progresses these developments will be incorporated in the release version of the software and this manual updated accordingly.

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Appendix A Original Structured Palisupan Geometry Input File

```
Line          Information                    Comments

1  0    1     0                              !      NB (I)  NLB (I) Dummy (I)
2  0.0    0.0    0.0           !      Reflection Plane Origin (V)
3  0.0    0.0    1.0           !      Reflection Plane Normal (V)
4  0.0    0.0    1.0           !      Dummy (V)
5  0.0    0.0    0.0           !      Origin of Axis of Rotation (V)
6  0.0    0.0    0.0           !      Axis of Rotation (V)
7  10.0                        !      Scale speed (m/s)
8  1        1   1              !      Nx(I)   Ny(I)   Nz(I)
9  0.0    0.0   0.0            !      Origin of Cuboid (V) (xo, yo, zo)
10 0.0       0.0  0.0          !      Increments (V) (dx,dy,dz)

For i = 1 to Nx*Ny*Nz          !      Loop data for all points
i1 -1.0  0.0    0.0            !(3)   Scaled Velocity (V)

For j = 1 to (NB+NLB)          !      Loop for all bodies then lifting bodies
j1 26  17    3    -1           !      Nt (I) Ns(I)  NS (I)  Image (I)
j2 16   5                             !      NoWake (I)      NoFree (I)       (1)
j3 4    0    1  0                     !      tdist(I), sdist(I), tclose(I),sclose(I)
j4 30.0     0.0     0.0        !      Pivot Vector (V)
j5 -0.0     0.0     0.0        !      Offset Vector (V)
j6 -0.00667  -0.0667  1.0      !      Scale Vector (V)
j7 0.0     0.0    0.0          !      Angles (V)

For k = 1 to NS                       !      Loop for all sections on body j
k1 35                                 !      NP (I)no of points in section

For l = 1 to NP                       !      Loop for all points in section k
   100.0   0.0      0.0        !      First point of section 1 (V)
   95.0    0.134    0.0
   90.0    0.241    0.0
   80.0    0.437    0.0
   70.0    0.611    0.0
   60.0    0.761    0.0
   50.0    0.882    0.0
   40.0    0.967    0.0
   30.0    1.0      0.0
   25.0    0.990    0.0
   20.0    0.956    0.0
   15.0    0.891    0.0
   10.0    0.78     0.0
   7.5    0.7     0.0
   5.0    0.592   0.0
   2.5    0.436   0.0
   1.25   0.316   0.0
   0.0    0.0     0.0
   1.25  -0.316   0.0
   2.5   -0.436   0.0
   5.0   -0.592   0.0
   7.5   -0.7     0.0
  10.0   -0.78    0.0
  15.0   -0.891    0.0
  20.0   -0.956    0.0
  25.0   -0.99     0.0
  30.0   -1.0      0.0
  40.0   -0.967    0.0
  50.0   -0.882    0.0
  60.0   -0.761    0.0
  70.0   -0.611    0.0
  80.0   -0.437    0.0
  90.0   -0.241    0.0
  95.0   -0.134    0.0
  100.0   0.0      0.0                !      Last point of section 1
  35                                         !      No. points in Section 2

For l = 1 to NP                       !      Loop for all points in section k 100.0    0.0
0.5                        !      First point of section 1
  95.0    0.134   0.5
  90.0    0.241   0.5
  80.0    0.437   0.5
  70.0    0.611   0.5
  60.0    0.761   0.5
  50.0    0.882   0.5
  40.0    0.967   0.5
  30.0    1.0     0.5
  25.0    0.990   0.5
  20.0    0.956   0.5
  15.0    0.891   0.5
  10.0    0.78    0.5
```

```
   7.5     0.7       0.5
   5.0     0.592     0.5
   2.5     0.436     0.5
   1.25    0.316     0.5
   0.0     0.0       0.5
   1.25   -0.316     0.5
   2.5    -0.436     0.5
   5.0    -0.592     0.5
   7.5    -0.7       0.5
  10.0    -0.78      0.5
  15.0    -0.891      0.5
  20.0    -0.956      0.5
  25.0    -0.99       0.5
  30.0    -1.0        0.5
  40.0    -0.967      0.5
  50.0    -0.882      0.5
  60.0    -0.761      0.5
  70.0    -0.611      0.5
  80.0    -0.437      0.5
  90.0    -0.241      0.5
  95.0    -0.134      0.5
  100.0    0.0        0.5                 !      Last point of section 2
  35                                             !      No. of points of Section 3

For l = 1 to NP                                  !      Loop for all points in section k 100.0
0.0      1.0                      !      First point of section 3
  95.0     0.134     1.0
  90.0     0.241     1.0
  80.0     0.437     1.0
  70.0     0.611     1.0
  60.0     0.761     1.0
  50.0     0.882     1.0
  40.0     0.967     1.0
  30.0     1.0       1.0
  25.0     0.990     1.0
  20.0     0.956     1.0
  15.0     0.891     1.0
  10.0     0.78      1.0
   7.5     0.7       1.0
   5.0     0.592     1.0
   2.5     0.436     1.0
   1.25    0.316     1.0
   0.0     0.0       1.0
   1.25   -0.316     1.0
   2.5    -0.436     1.0
   5.0    -0.592     1.0
   7.5    -0.7       1.0
  10.0    -0.78      1.0
  15.0    -0.891      1.0
  20.0    -0.956      1.0
  25.0    -0.99       1.0
  30.0    -1.0        1.0
  40.0    -0.967      1.0
  50.0    -0.882      1.0
  60.0    -0.761      1.0
  70.0    -0.611      1.0
  80.0    -0.437      1.0
  90.0    -0.241      1.0
  95.0    -0.134      1.0
  100.0    0.0        1.0                 !      Last point of section 3 (V)
   4                                             !(2) No points on 1st wake section (I)

For l = 1 to NP                           !      Loop for all points in wake section k 100.0  0.0
     0.0                          !      First wake point, section 1 (V)
   125.0  0.0        0.0
   150.0  0.0        0.0
   250.0  0.0        0.0                  !      Last wake point, section 1 (V)
   4                                             !      No points on 2nd wake section (I)

For l = 1 to NP                           !      Loop for all points in wake section k 100.0  0.0
     0.5                          !      First wake point, section 2 (V)
   125.0  0.0        0.5
   150.0  0.0        0.5
   250.0  0.0        0.50                        !      Last wake point, section 2 (V)
4                                                !      No points on 3rd wake section (I)

For l = 1 to NP                           !      Loop for all points in section k
100.0  0.0        1.0                     !      First wake point, section 3 (V)
   125.0  0.0        1.0
   150.0  0.0        1.0
   250.0  0.0        1.00                        !      Last wake point, section 3 (V)
```

NOTES

A standard ASCII text format is used. The first line defines the number of non-lifting bodies and lifting bodies. Then, a plane of symmetry and the necessary axis and rate of rotation if required (otherwise dummy values must be used).

The velocity field is specified as a uniform distribution of points, Nx, Ny, and Nz in the overall cartesian or cylindrical axes system directions. At each point, a scaled velocity vector is given relative to a defined inflow speed.

The definition of non-lifting and lifting bodies is carried out in order. For each body the pivot, offset, scale and angle of its own body centred axis system is given as described in the main report. Each body is defined by a variable number of sections, and each section consists of a variable number of points. Also given are the number of spanwise and chordwise panels for the body. Two parameters define the type of panel size distribution on the body. Example distributions allow clustering of panels at body leading and trailing edges using various forms of sinusoidal function.

For the lifting surface bodies additional information is given to describe the trailing edge wake sheet in a manner similar to that of the body itself. The example lifting surface body definition, with comments, is given below for a typical ship rudder. Additional comments are given below.

Parameters indicated by (I) need to be integer values and those indicated by (V) need to consist of three real numbers i.e. a vector quantity. Also line numbers and comments must not be included in file.

(1) This line omitted when defining a non-lifting body
(2) No wake sections defined for a non-lifting body
(3) Velocity field information is ordered in the manner shown below

```
for i = 0 For Nx
    for j=0 For Ny
        for k=0 For Nz
            Vx[i][j][k], Vy[i][j][k], Vz[i][j][k]
```

and each velocity is located at the following coordinates

$$x = xo + i * dx$$
$$y = yo + j * dy$$
$$z = zo + k * dz$$

A cylindrical velocity field is designated by the z component of the index increment (dz) having a value greater than 10,000. The origin of the axis is taken to be xo, yo, zo, and the unit vector in the axis direction **A** is defined thus:

$$A.x = dz - 10000$$
$$A.y = Vy[0][0][0]$$
$$A.z = Vz[0][0][0]$$

dx is the increment in the axial direction , and dy the increment in radial direction (dr). Nz is always equal to one, and Vy corresponds to the radial velocity (positive outwards) and Vz the velocity on the circumferential direction Vw. The direction of Vw is determined by the cross product **A x (0,0,1)**

Important Variables

NB Number of non-lifting bodies i.e. a body which does not develop circulation

NLB Number of lifting bodies i.e. bodies with a prescribed wake from a definite trailing edge

Nt Number of nodes in t (section or usually chordwise direction), number of panels is Nt - 1

Ns No. of nodes in s (usually spanwise direction), number of panels is Ns - 1.

NS Number of sections used to define body at least 3 sections are required for each body.

Image = 0 {no reflection plane }, = -1 { ref;lection plane located at defined origin and with defined outward facing normal }, = +N { no. degrees of rotational symmetric bodies, 1 is just defined body, > 1 is 1 body at N-1 images at a spacing of 360°/N, origin and rotational axis of symmetry are given at start of file}.

NoWake Is total number of nodes used to panellise wake sheet strip, of which there will be (Ns-1), second integer

NoFree is the number of wake panels which are allowed to move in wake adaptation process.

tdist is the type of panel size distribution in the t direction

sdist is the type of panel size distribution in the s direction

At present the allowed mappings for the t and s directions are as follows

0 Equal sized panels

1 Sinusoid clustering as parameter tends to 1

2 Sinusoid clustering as parameter tends to 0 and unity

3 Sinusoid clustering as parameter tends to 0, 0.5 and 1

4 Sinusoid clustering as parameter tends to 0.5

5 Sinusoid clustering as parameter tends to 0

6 Modified sinusoid clustering as parameter tends to 0 with minimum size of 0.25Δ

7 Modified sinusoid clustering as parameter tends to 0 with minimum size of 0.5Δ

8 Special parameter for splitting section with two specified break points

9 Even clustering in the x direction

10 Even clustering in the y direction

11 Even clustering in the z direction

Distribution

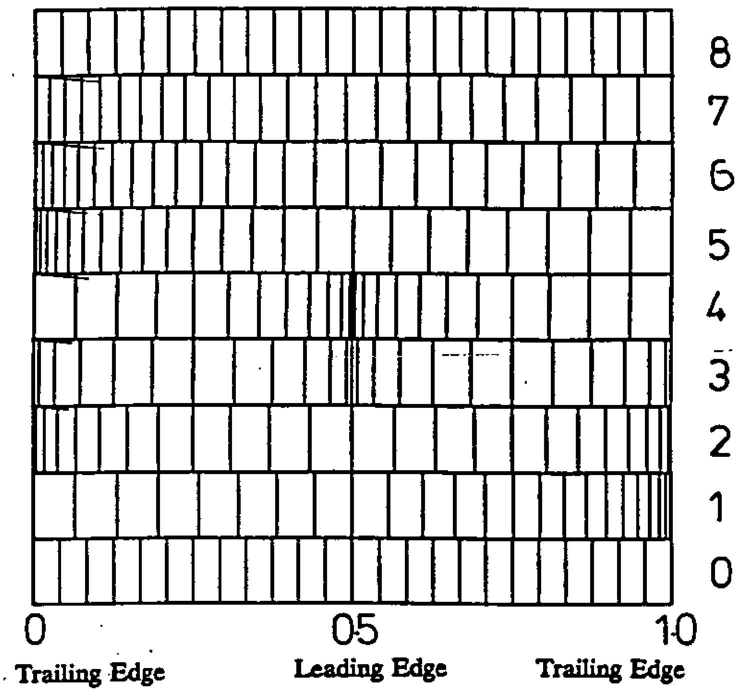

Figure A Sample clustering

tclose Value of 1 states that the sections are closed and 0 they are open
sclose Value of 1 states that the sections are closed and 0 they are open

Appendix B New Fleximesh Unstructured File Format

The fleximesh definition is stored as ascii text and has five sections:

1. Problem data, which stores information about the overall problem
2. Body data, which gives information about each of the bodies describing the problem
3. Panel Data, which defines all the panels and their node and body mappings
4. Node Data, which defines all the nodes used as x,y,z values in the overall coordinate frame
5. Velocity, which define a spatially varying velocity field as per original format

1 Problem Data

Line 1: I_NoBodies I_NoNodes I_TotNoPan I_NoTEPans
Line 2: I_NoDSPans I_NoFreeW I_NoFixW I_NoSource I_NoDipole
Line 3: R_RP.x R_RP.y R_RP.z
Line 4: R_n.x R_n.y R_n.z
Line 5: R_axis.x R_axis.y R_axis.z
Line 6: R_origin.x R_origin.y R_origin.z

2 Body Data

Repeat for i =1 to NoBodies

Line i:1	I_BodyType I_Reflect I_Rotation I_moved I_interaction
Line i.2:	R_offset.x R_offset.y R_offset.z
Line i:3:	V_scale
Line i:4:	V_pivot
Line i:5	V_angle
Line i:6	V_speed
Line i:7	V_omega
Line i:8	V_axisorigin
Line i:9	V_centre
Line i:10	R_density, R_viscosity R_mass

3 Panel Data

{ repeat i=1 for TotNoPan Absolute Panel No is defined by order in which it appears in this list}

Line i:1	I_Nsides I_type I_BodyNo
Line i:2	for j=1 to N_sides: I_NodeId[j]
Line i:3	for j=1 to N_sides: I_CellSides[j]
Line i:4	R_strength R_cp
Line i:5	V_Velocity

4 Node Data

{ repeat i=1 to TotNoNodes } Absolute Node Number defined by order in which it appears in list

Line i:1 V_Node

5 Velocity Data

Line 1 R_Vscale
Line 2 I_Nx I_Ny I_Nz
Line 3 V_origin
Line 4 V_inc

```
{for i = 1 to I_Nx}
        {for j=1 to I_Ny }
                {for k=1 to I_Nz }
                        Line i:j:k:1    V_Velocity
```

Appendix C Palisupan Data Structure

```
/* PALISUPAN header file including structures */
/* written S.R. Turnock 14/6/95 */

/* define libraries */

#include <stdio.h>
#include <math.h>
#include <stdlib.h>

/* define system constants */

#define SQR(a) ((a)*(a))
#define pi 3.141592654
#define MaxSide 5
#define Dim 100
#define TNP 100
#define TNB 10
#define TNV 100
#define TNS 30
#define MaxSpline 100

/* define structures */

struct vect3 {
    double x,y,z;
    };

struct threemat {
     struct vect3 C[3];
   };

struct matrix{
  double mat[Dim*Dim];
  int Msize;
};

struct vector
{
  double vec[Dim];
  int Vsize;
};


struct vect3 {
    double x,y,z;
    };
```

```
struct threemat {
      struct vect3 C[3];
    };

struct nodes{
      struct vect3 nd[TNN];
};

struct panel{
     int Nsides,type,BodyNo;
     int NodeId[MaxSide],CellSides[MaxSide];
     double strength,cp;
     struct vect3 V;
};

struct AllPanel{
     struct panel pan[TNP];
};

struct body{
     struct vect3 offset,scale,pivot,angle,speed,omega,axisorigin,centre;
     int BodyType,Reflect,Rotation,moved,interaction;
     double density,viscosity,mass;
};

struct AllBody{
     struct body bod[TNB];
};

struct ProblemData{
     struct vect3 RP,n,ax,oax;
     int NoBodies;
     int
NoNodes,TotNoPan,NoTEPans,NoDSPans,NoFreeW,NoFixW,NoSource,NoDipole;
};

struct Velocity{
     struct vect3 Vmin,Vinc;
     double Vref;
     int Nx,Ny,Nz;
     struct vect3 Vps[TNV];
};

struct Geometry{
     struct ProblemData PD;
     struct AllPanel AP;
     struct AllBody AB;
     struct Velocity Vel;
     struct nodes ND;};
```

Appendix D Keel-Bulb geometry input file

```
0       2       0
0       0       0
0       0       1
0       0       1
0       0       0
0       0       0
40
1       1       1
0       0       0
0       0       0
1       0       0
26      9       3       -1
25      10
4       0       1       0
200     0       0
0       0       0
0.001   0.001   0.001
0       0       0
51
480     0       -660
460     2.54    -660
440     5.51    -660
420     8.7     -660
400     11.59   -660
380     14.49   -660
360     17.68   -660
340     20.87   -660
320     23.77   -660
300     26.09   -660
280     27.83   -660
260     28.99   -660
240     29.56   -660
220     29.28   -660
200     28.7    -660
180     27.54   -660
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373.5493	40.57655	-732.0001
335.3342	46.73595	-732.0001
297.1176	50.04438	-732.0001
259.8473	49.40752	-732.0001
224.4395	45.06679	-732.0001
191.7631	38.00267	-732.0001
162.6212	29.35648	-732.0001
137.7314	20.30718	-732.0001
117.7066	12.3788	-732.0001
103.0402	10.29814	-732.0001
94.09349	5.112059	-732.0001
91.14436	0	-732.0001
94.09349	-5.112059	-732.0001
103.0402	-10.29814	-732.0001
117.7066	-12.3788	-732.0001
137.7314	-20.30718	-732.0001
162.6212	-29.35648	-732.0001
191.7631	-38.00267	-732.0001
224.4395	-45.06679	-732.0001
259.8473	-49.40752	-732.0001
297.1176	-50.04438	-732.0001
335.3342	-46.73595	-732.0001
373.5493	-40.57655	-732.0001
410.8125	-33.04778	-732.0001
446.1936	-25.59097	-732.0001
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576.1635	-0.5558975	-732.0001
579.1575	-0.01850595	-732.0001
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527.6944	2.425672	-720
514.3023	5.39952	-720
496.0015	9.453291	-720
473.2252	14.47683	-720
446.5122	20.33016	-720
416.4967	26.84488	-720
383.9097	33.6652	-720
349.5707	39.94033	-720
314.3481	44.62843	-720
279.1295	46.74103	-720
244.7909	45.66386	-720
212.1723	41.61883	-720
182.0707	35.24509	-720
155.2251	27.40173	-720
132.2957	19.07757	-720
113.8479	11.71691	-720
100.3365	9.485977	-720
92.09424	4.508634	-720
89.38429	0	-720
92.09424	-4.508634	-720
100.3365	-9.485977	-720
113.8479	-11.71691	-720
132.2957	-19.07757	-720
155.2251	-27.40173	-720
182.0707	-35.24509	-720
212.1723	-41.61883	-720
244.7909	-45.66386	-720
279.1295	-46.74103	-720
314.3481	-44.62843	-720
349.5707	-39.94033	-720
383.9097	-33.6652	-720
416.4967	-26.84488	-720
446.5122	-20.33016	-720
473.2252	-14.47683	-720
496.0015	-9.453291	-720
514.3023	-5.39952	-720
527.6944	-2.425672	-720
535.8597	-0.6102608	-720
538.6042	-0.0220925	-720
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369.1758	32.40791	-708
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302.653	41.56774	-708
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236.141	42.34713	-708
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517.0898	-0.02331227	-708
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481.3974	5.224017	-696
464.3244	9.118374	-696
443.0836	13.86724	-696
418.1808	19.2253	-696
390.211	24.85695	-696
359.8611	30.28839	-696
327.8905	34.94183	-696
295.1024	38.2386	-696
262.3183	39.69328	-696
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199.9875	36.13508	-696
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146.9759	25.11718	-696
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453.4083	8.879729	-684

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382.4951 22.9711 -684
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289.2085 34.86025 -684
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93.81175 7.613493 -684
86.28645 2.944409 -684
83.84042 0 -684
86.28645 -2.944409 -684
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289.2085 -34.86025 -684
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382.4951 -22.9711 -684
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455.2028 -8.500629 -684
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448.5033 7.600619 -672.0001
427.8817 11.57009 -672.0001
403.7256 16.06766 -672.0001
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347.2414 25.3584 -672.0001
316.3077 29.19557 -672.0001
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460 2.54 -660
440 5.51 -660
420 8.7 -660
400 11.59 -660
380 14.49 -660
360 17.68 -660
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320 23.77 -660
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180 27.54 -660
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1500 0 -840
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825.7521 0 -828.0001
1021.3 0 -814.9
1500 0 -828
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805.2381 0 -816
1004.5 0 -803.7
1500 0 -816
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784.9334 0 -804
987.09 0 -792.6
1500 0 -804
3
764.9179 0 -792.0001
968.08 0 -780
1500 0 -792
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744.891 0 -780
946.48 0 -765
1500 0 -780
3
723.7289 0 -768
855 0 -746.1
1500 0 -763.3
3
697.9053 0 -756
806 0 -733
1500 0 -750.4
3
648.8679 0 -744
728 0 -713
1500 0 -732
3
579.1575 0 -732.0001
702 0 -697
1500 0 -704
3
538.6042 0 -720

671	0	-683
1500	0	-689
3		
517.0898	0	-708
663	0	-663.6
1500	0	-671
3		
504.0773	0	-696
634	0	-642.1
1500	0	-650
3		
494.2629	0	-684
630	0	-622.3
1500	0	-627
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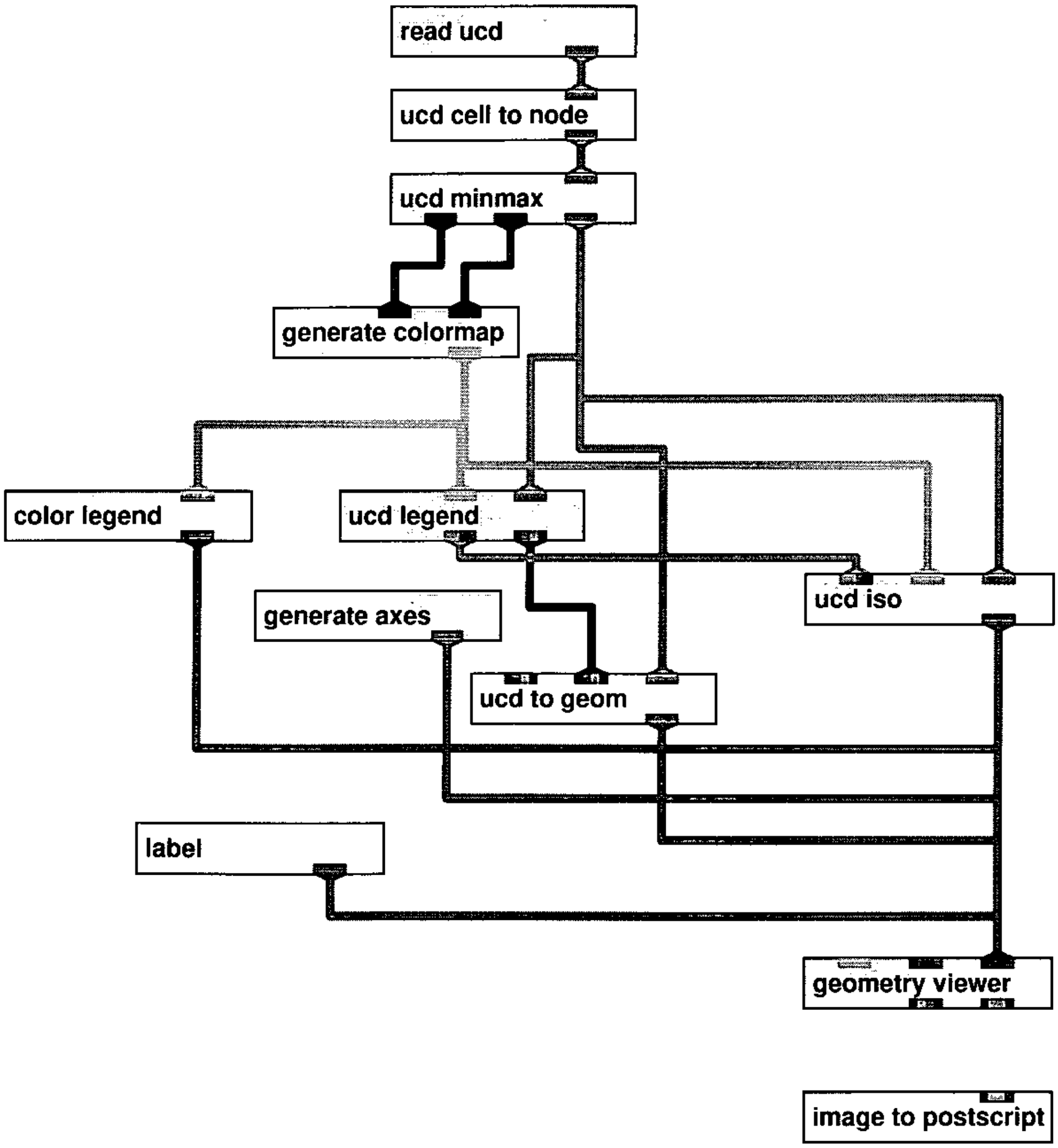
487.1314	0	-672.0001
622	0	-598
1500	0	-582
3		
480	0	-660
617	0	-540
1500	0	-514

Appendix E Representative AVS Network



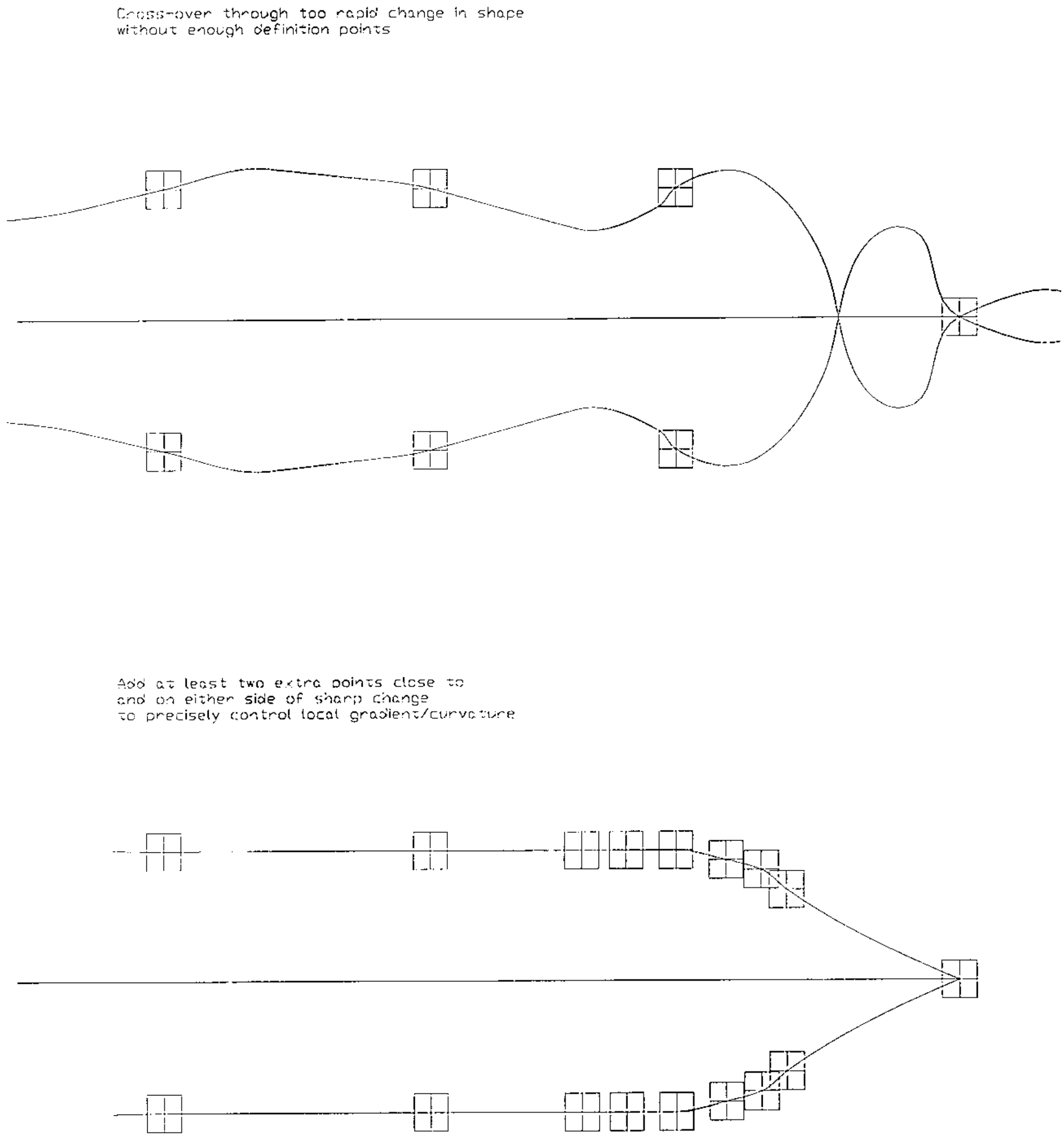


Figure 3 Cure of Problems with Spline Crossover

Figure 4 Basis keel-bulb geometry and equivalent fin

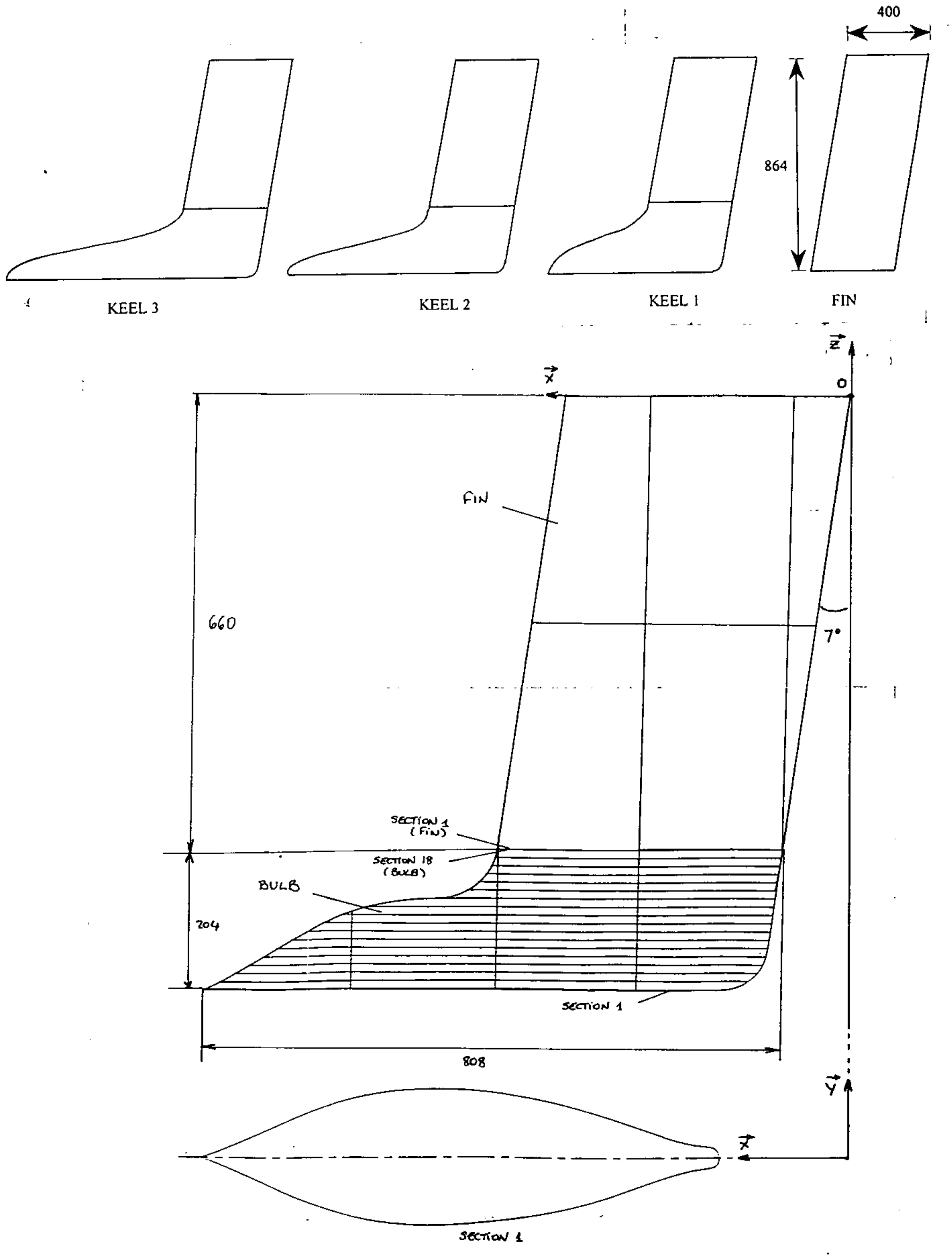


Figure 5 Experimental Data for Keel-Bulb Combination, Side force vs. Incidence

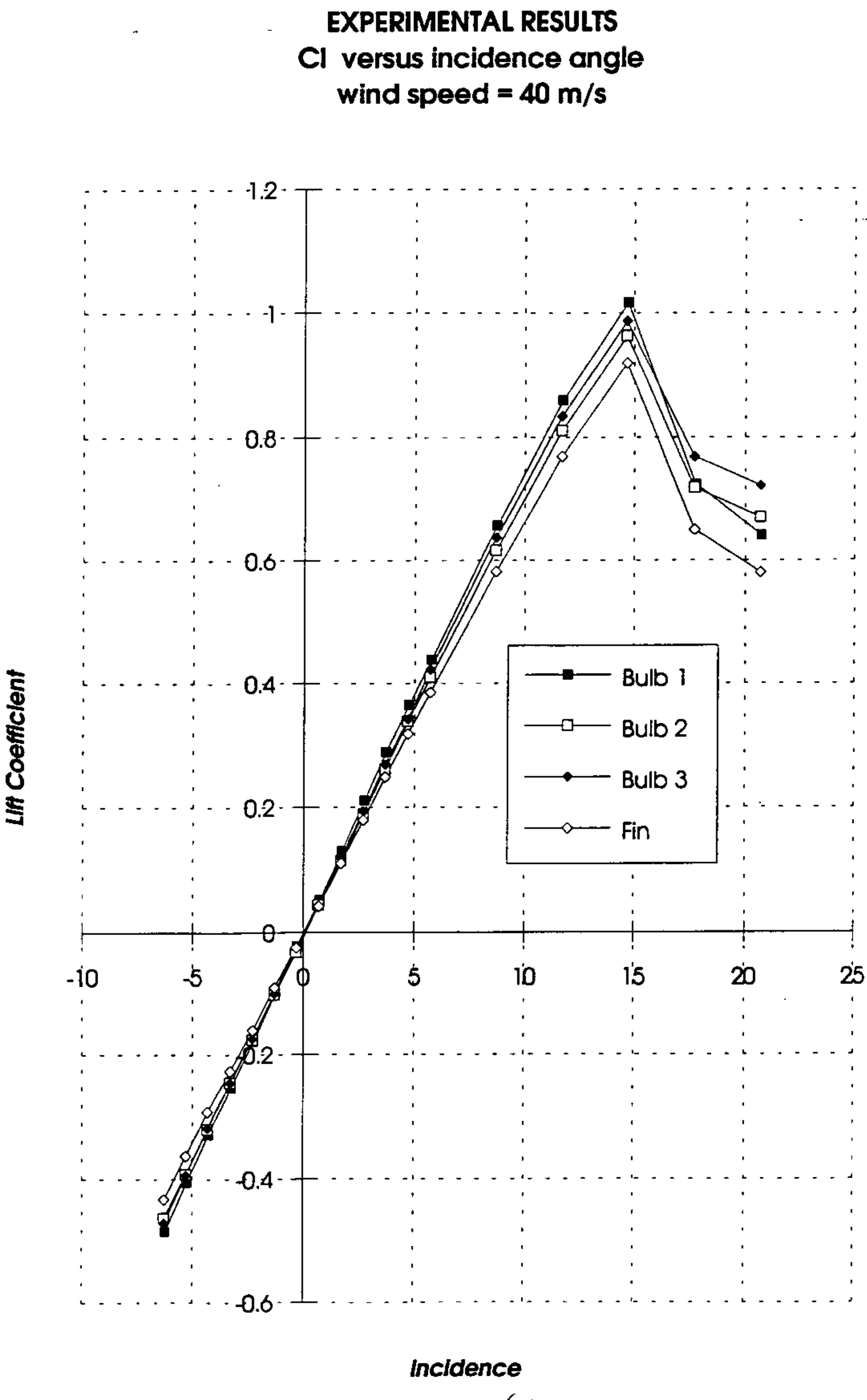


Figure 6 Experimental Data for Keel-Bulb Combination, Drag vs. Incidence

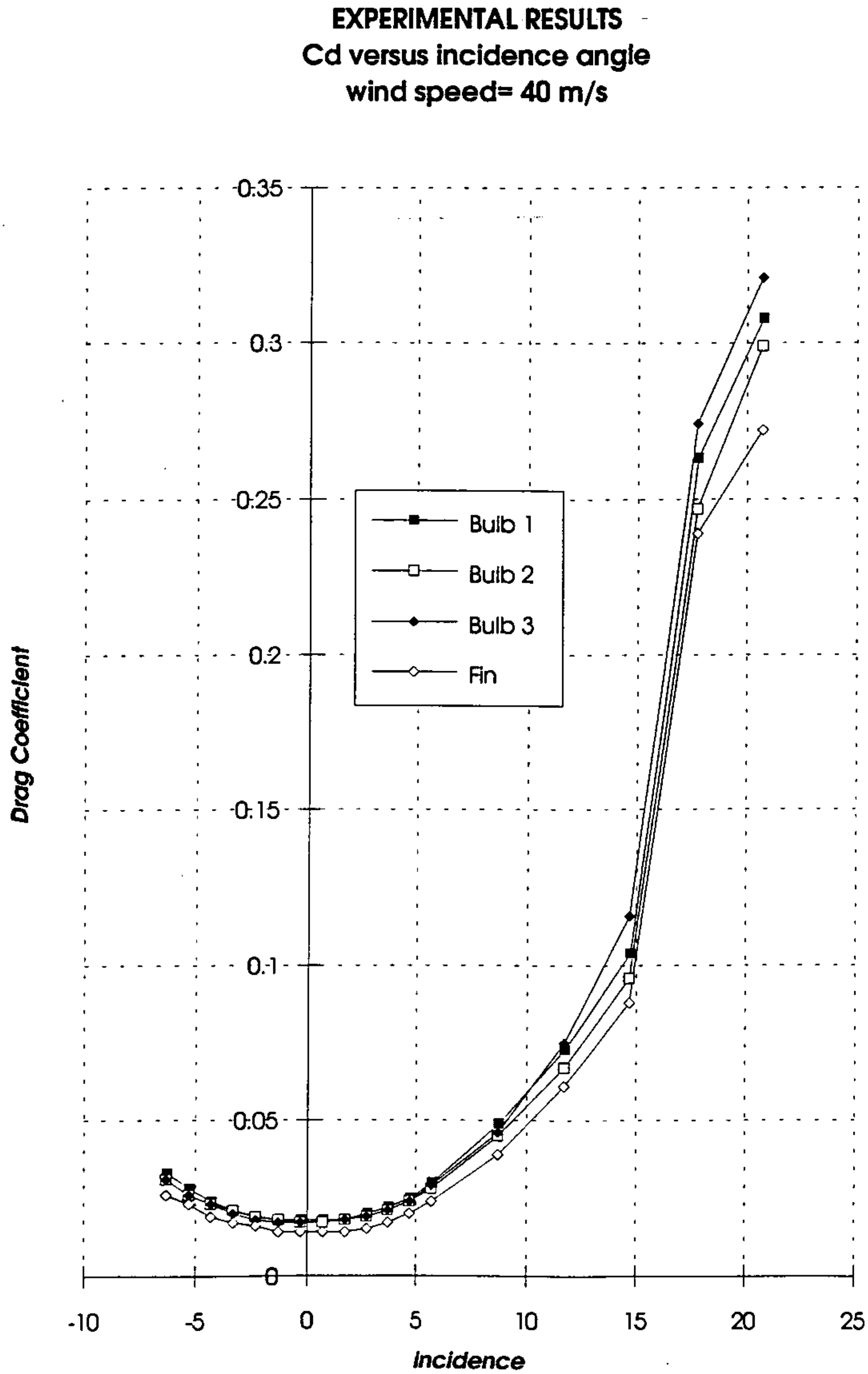


Table 1 Freestream Rudder Performance Data at 10 m/s

RUDDER DYNAMOMETER
epfsv136.rud Free-stream Rudder No. 2 10m/s

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-40.00	10.00	0.00	-0.5610	-0.789	0.559	-0.070	-0.3870	0.2590	38.879	41.147
-35.00	10.00	0.00	-0.5270	-0.694	0.459	-0.051	-0.3630	0.2190	37.339	43.338
-30.00	10.00	0.00	-0.4930	-0.618	0.382	-0.040	-0.3340	0.1910	36.486	44.669
-25.00	10.00	0.00	-0.8500	-0.871	0.239	0.020	-0.5960	0.1230	27.683	50.451
-20.00	10.00	0.00	-0.9260	-0.927	0.167	0.055	-0.6160	0.0840	24.100	48.039
-15.00	10.00	0.00	-0.7510	-0.751	0.099	0.059	-0.4880	0.0510	22.183	46.934
-10.00	10.00	0.00	-0.4980	-0.500	0.056	0.047	-0.3150	0.0280	20.501	45.587
-5.00	10.00	0.00	-0.2370	-0.239	0.031	0.027	-0.1490	0.0150	18.881	45.044
0.00	10.00	0.00	0.0097	0.010	0.018	0.002	0.0150	0.0110	48.595	173.486
5.00	10.00	0.00	0.2500	0.251	0.023	-0.022	0.1770	0.0150	21.277	53.319
10.00	10.00	0.00	0.4930	0.494	0.045	-0.042	0.3400	0.0260	21.383	51.158

RUDDER DYNAMOMETER
epfsv236.rud Free-stream Rudder No. 2 20m/s

Angle	V	RPM	Cl	Cn	Cd	Cmz	Cmx	Cmy	Cpc	Cps
-15.00	20.00	0.00	-0.7720	-0.768	0.087	0.060	-0.4970	0.0630	22.203	47.165
-10.00	20.00	0.00	-0.5120	-0.513	0.047	0.044	-0.3250	0.0360	21.405	46.130
-5.00	20.00	0.00	-0.2470	-0.249	0.024	0.023	-0.1520	0.0190	20.842	44.047
-4.00	20.00	0.00	-0.1980	-0.199	0.022	0.019	-0.1190	0.0160	20.667	42.917
-3.00	20.00	0.00	-0.1470	-0.148	0.020	0.014	-0.0870	0.0150	20.475	41.833
-2.00	20.00	0.00	-0.0940	-0.094	0.018	0.009	-0.0530	0.0130	20.233	39.164
-1.00	20.00	0.00	-0.0400	-0.041	0.017	0.004	-0.0190	0.0120	19.349	30.358
0.00	20.00	0.00	0.0083	0.008	0.017	-0.001	0.0130	0.0123	17.328	163.675
1.00	20.00	0.00	0.0560	0.056	0.016	-0.006	0.0450	0.0120	19.825	63.009
2.00	20.00	0.00	0.1090	0.110	0.017	-0.011	0.0790	0.0130	20.357	54.706
3.00	20.00	0.00	0.1580	0.159	0.018	-0.016	0.1100	0.0140	20.081	52.183
4.00	20.00	0.00	0.2110	0.212	0.020	-0.021	0.1450	0.0150	20.291	51.011
5.00	20.00	0.00	0.2620	0.263	0.022	-0.025	0.1770	0.0170	20.340	49.970
10.00	20.00	0.00	0.5190	0.519	0.045	-0.045	0.3460	0.0310	21.269	49.170
15.00	20.00	0.00	0.7820	0.778	0.086	-0.060	0.5200	0.0590	22.278	49.060
20.00	20.00	0.00	1.0040	0.996	0.152	-0.054	0.6800	0.1040	24.547	50.225
25.00	20.00	0.00	0.8190	0.845	0.245	0.001	0.5700	0.1620	30.149	51.706
30.00	20.00	0.00	0.7680	0.819	0.307	0.017	0.5400	0.2070	32.012	52.288
35.00	20.00	0.00	0.6980	0.854	0.492	0.052	0.4970	0.3230	36.028	51.834
40.00	20.00	0.00	0.5890	0.814	0.565	0.079	0.4210	0.3590	39.675	50.473
45.00	20.00	0.00	0.6030	0.891	0.658	0.095	0.4260	0.4250	40.692	50.038
50.00	20.00	0.00	0.5960	0.964	0.758	0.124	0.4340	0.4960	42.842	50.884
55.00	20.00	0.00	0.5750	1.063	0.895	0.149	0.4300	0.5690	43.998	49.563
60.00	20.00	0.00	0.5580	1.155	1.011	0.165	0.4130	0.6400	44.310	48.361
65.00	20.00	0.00	0.4940	1.233	1.130	0.197	0.3820	0.7060	45.990	47.482
70.00	20.00	0.00	0.4150	1.289	1.220	0.227	0.3350	0.7580	47.595	46.670

Table 2 Spanwise Lift Coefficients

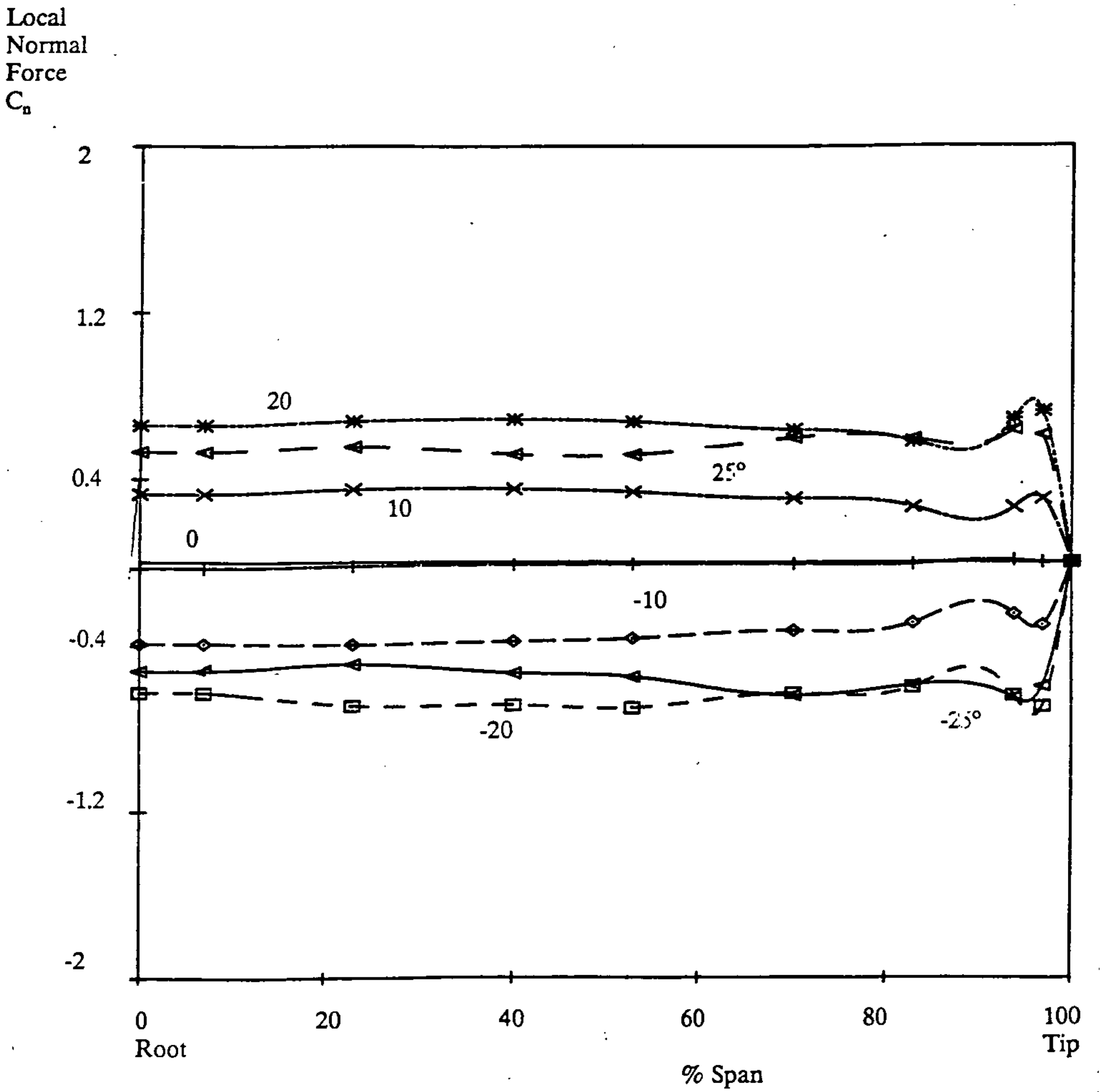


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Table 3 Freestream Surface Pressure Data