A Transputer based Parallel Algorithm for Surface Panel Analysis

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SUMMARY

A surface panel method has been developed to run in parallel across variable sized square arrays of transputers. A geometric parallelism is used for both the data distribution and the algorithm. A flexible geometry definition allows complex three-dimensional surfaces and multiple body problems to be solved. Each body surface is sub-divided into quadrilateral panels. A fast parallel block-iterative solver was developed which allows rapid solution of the dense but diagonally dominant linear system of equations. The parallel performance of the surface panel code is described and the necessary scaling of number of transputers and distributed memory per transputer to obtain solutions of surface panel problems of order of 10,000 panels is given. A final section gives, as an example, the use of the code in predicting ship rudder-propeller interaction.

1. INTRODUCTION

The use of surface panel methods for modelling potential flow around marine vessels is widespread. For the hydrodynamicist they provide a valuable tool capable of reasonable prediction of body forces without extravagant use of computational time. However, for larger problems involving detailed three-dimensional surfaces and multiple body problems the required computational time still restrict their use.

In general surface panel techniques are solved using implicit techniques which require the calculation of coefficients for a dense matrix and then the solution of a large linear system of equations. Parallel algorithms are easily produced for explicit schemes however there is a need for research into the ways in which the benefits of parallel processing can be applied to implicit algorithms such as the surface panel method. The work reported is part of a research programme to investigate ship rudder-propeller interaction and further details can be found in Molland (1992 a,b).

The implementation of a lifting surface panel method to run on an array of transputers using the developed communications harness is described. A suite of procedures for carrying out the various stages of the analysis has been written and is referred to as the PALISUPAN (**PA**rallel **LI**fting **SU**rface **PA**nel) code. A geometric parallelism was used for the data distribution and the numerical formulation of PALISUPAN. The parallelism is based on equally dividing the total number of lifting surface and wake panels amongst the numbers of transputers available on a given parallel computer.

An important parameter in parallel processing is the measurement of the performance of a particular parallel algorithm on a given parallel computer. How this is quantified and how performance is compared to that of an equivalent serial algorithm are necessary questions in determining whether transputer based parallel computers provide a cost-effective method for carrying out a particular application.

All the software was written in Occam2. The overall software design philosophy was to minimise the development time and subsequent debugging by the use of simple geometric algorithms. A structured approach making full use of the procedures and channel communications of Occam2 allowed this to be successfully carried out.

A variety of methods can be used to produce parallel algorithms to solve a lifting surface panel problem with a total of N panels using T transputers. A parallel geometric algorithm where each transputer is assigned (N/T) panels is the simplest method and is one which naturally lends itself to the solution of computational fluid dynamic problems. Also, problems with different total number of panels can be easily scaled without the need to alter the software simply assigning a different number of panels to each transputer.

2. TRANSPUTERS

The transputer is a micro-processor based integrated circuit designed as a basic building block for the construction of both large and small scale parallel computers. Associated with the transputer is Occam2: a computer language specifically developed to make full use of the parallel processing capabilities of the transputer.

Transputers are a range of high-performance VLSI(Very Large Scale Integrated) technology devices, developed by Inmos Ltd, which consist of local memory, four high speed two-way links and a micro-processor unit all mounted on a single silicon chip. The provision of high speed communication links allows transputers to be connected together to produce a parallel processing computer. There are no limits to the number of transputers which can be connected together in a network. The only restriction is in the topology of the parallel machine. Each transputer can be connected to a maximum of four. Massively parallel machines can be built up from large numbers of transputers.

Parallel computers are classed according to the number of tasks (or instructions) and number of data streams they can process simultaneously. Transputer based machines belong to the most general class of Multiple-Instruction-Multiple-Data stream (M.I.M.D.) machines. The advantage of transputer based parallel processing systems is that the same basic processing unit can be used for both small-scale and large-scale computational applications. Code can be developed on inexpensive machines with a small number of transputers and then executed on a large array of transputers.

The performance of transputer based parallel computers can be scaled if all the component transputers have identical computational and communication loads. This facility allows parallel computers which use small numbers of transputers to be used to assess the performance of large scale computations. An important proviso is that an appropriate scale of problem size is used. As an example of such a study Robinson (1990) investigated the parallelism of a commercial fluid dynamics software package ASTEC, Lonsdale (1989), which uses an implicit finite volume solution method on a finite element mesh. They concluded that transputer based parallel systems can deliver greatly increased performance and also that parallel systems allow problems to be solved which could not be tackled on sequential machines.

3. SURFACE PANEL 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 (1990). Lamb(1932) 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 σ and a normal dipole distribution per unit area μ 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:

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

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.

The conditions imposed on the disturbance potential are that:
1) the velocity potential satisfies Laplace's equation everywhere outside 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.

The numerical procedure used is based on that of Morino (1974) where the body surface is represented 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.
On the body surface the source strength per unit area is prescribed by satisfying the condition for zero normal velocity at the panel centroid:

$$\sigma_S = \bar{U} \cdot \bar{n} \qquad [4]$$

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 [3] gives the potential at the centroid of panel i as:

$$\phi_i = \frac{1}{2\pi} \sum_{j=1}^{N} \left((U \cdot n_j) S_{ij} - \phi_j D_{ij} \right) + \sum_{k=1}^{M} \Delta\phi_k W_{ik} \qquad [5]$$

where for panel j: S_{ij} is the source influence coefficient of a unit strength panel; D_{ij} the dipole influence coefficient; and 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, [5] is closed and can be evaluated. Expressed in matrix form it becomes:

$$[\, D_{ij} \,]\, \underline{\phi} + [\, W_{ik} \,]\, \underline{\Delta\phi} = [\, S_{ij} \,]\, (U \cdot n) \qquad [6]$$

The original Morino trailing edge Kutta condition, specified the wake strength $\Delta\phi$ as the difference in trailing edge panel potential, the matrix expression [6] can then be directly solved to give the vector of dipole potentials $\boldsymbol{\phi}$. Numerical differentiation of dipole potential along the body surface allows the surface velocity and hence pressures on the surface to be evaluated.

The methods used for the evaluation of the individual influence coefficient elements of the matrices S_{ij}, D_{ij} and W_{ik} are based on those described by Newman (1986).

For most three-dimensional geometries there is a cross-flow at the trailing edge and this requires an iterative approach to determine the correct wake strength by ensuring that the pressure difference Δp between the upper and lower panels at the trailing edge is zero. As Δp is primarily a function of the local trailing edge wake sheet strength $\Delta\phi$ an iterative Newton-Raphson approach is used (Lee 1987) to determine the wake strength for the point of zero pressure difference at the trailing edge. Once the solution vector $\boldsymbol{\phi}$ is obtained this is used to calculate Δp at the trailing edge. The 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 the original matrix expression to:

$$[\, D_{ij} + W_{ik} \,]\, \phi = [\, S_{ij} \,]\, U \cdot n_j - [\, W_{ik} \,] \left[\frac{d\Delta\phi}{d\Delta p} \Delta p \right]^k \qquad [7]$$

where the wake strength for k=0 is taken to be the difference in potential between the trailing edge panels. The process is repeated until the pressure loading at the trailing edge has been removed.

The numerical solution gives a result vector which specifies a dipole strength at the centre of each panel. 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. Once this velocity is determined the surface pressure and hence total body force can be evaluated.

4. SURFACE GEOMETRY DEFINITION

The ease with which the geometry of a lifting-surface problem can be distributed across the array of transputers will determine the usefulness of the fluid dynamic code.

In this work one of the principal features is the investigation of the performance of a lifting-surface code on a transputer network. Therefore, it is necessary to have a simple means of scaling the overall problem size by altering the number of panels used to define a lifting-surface. The decision was made to generate the actual panel vertex coordinates within the program but to 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.

A useful 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 defined in terms of a single parameter. Defining the value of the parameter uniquely defines the value of a point on the line. The parameter is the arc distance along the original curve and is usually approximated as the straight-line distance between points used to define the line. 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 was that of zero curvature.

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.