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Computer system for calculation of flow, resistance and propulsion of a ship at the design stage

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Abstract

The computer system executable on personal computers enables determination of flow parameters of a ship with or without a propeller. The system is based on a potential solution of the three- dimensional flow around the hull, taking into account the free water surface. The basis of solution is determination of the distribution of Rankine type singularities on the double hull surface discretized by a number of flat panels. After solving the linear boundary condition the system of ship generated waves is obtained through a transformation of the Bernoulli waves. This transformation is based on an original solution of the Green function for a single pressure pulse and equally original method of superposition of such solutions. The propeller is modelled by lifting surface theory and its interaction with the ship is taken into account by including propeller induced velocity in the boundary condition on the hull. The propeller loading is determined by evaluation of total resistance, thrust deduction and wake fraction using a procedure based on theoretical and empirical relations.

The system enables determination of the total and wave resistance, wave profile on waterline, streamlines and pressure distribution on the hull surface, wave system on the free surface for a ship model moving with constant speed on calm water.

1 Introduction

The article presents description of the computer system for the resistance, propulsion and flow analysis of ships. Currently the system is in the process of development, the potential flow stage has been completed, the viscous flow and propeller-hull interaction stage is being developed and tested. In its current form the system may supply the following information : streamlines on the hull, static pressure distribution on the hull, wave profile along the waterline, wave system on the free surface and the value of wave resistance. The system is composed of a large number of subroutines organised into four calculation modules, one data input module and four modules for graphical presentation of the results. All elements of the system are written in FORTRAN77. Calculation may be performed on Iris Indigo (Silicon Graphics) workstation or IBM compatible PC's 486/16Mb RAM.

2 Theoretical background

The case of a surface ship, moving with constant velocity and straight course on the initially undisturbed flat water surface is considered. The analysis is performed in the Cartesian system of co-ordinates with OX axis located in the ship plane of symmetry pointing towards stern, OY axis pointing to starboard and OZ axis pointing vertically down. The origin of the system lies on the water surface in the middle of the hull length between perpendiculars Lpp. The flow is stationary and irrotational, water being considered incompressible. The water is regarded as unlimited for $z > \zeta$.

The flow around the ship is described through the velocity potential $\Phi(x,y,z)$, which fulfils the Laplace equation:

$$\nabla^2\Phi = 0 \qquad (1)$$

The kinematic boundary condition postulating no flow through the hull surface must be fulfilled on this surface:

$$\left.\frac{\partial\Phi}{\partial n}\right|_S = V_s \cdot n_x \qquad (2)$$

Two more boundary conditions should be fulfilled on the free water surface $z=\zeta$ (x,y), where ζ denotes the height of waves generated by the moving ship.

The kinematic condition requests no flow through the free water surface:

$$\Phi_x\zeta_x + \Phi_y\zeta_y - \Phi_z = 0 \qquad (3)$$

The dynamic boundary condition requires equilibrium of pressure on the free water surface:

$$(\nabla\Phi)^2 - 2g\zeta = V_s^2 \qquad (4)$$

Additionally it is assumed that the disturbance of water generated by the moving ship is fading at infinity and that the water surface tension may be neglected. The process of solution starts from the analysis of flow around a "double" hull, assuming that the free water surface is a rigid flat wall.

The velocity potential Φ is generated by a system of mathematical singularities 1/r (Rankine sources), distributed on the hull wetted surface S and on the surface of its mirror image. It may be expressed as:

$$\Phi(x,y,z) = \iint \frac{\sigma(q)}{r(p,q)} dS + n_x \cdot V \qquad (5)$$

used for tracing of the streamlines, calculation of pressure and estimation of the wave system on the free surface.

The unknown ζ in equations (3) and (4) may be eliminated, leading to the non-linear boundary condition for the deformed water surface around the ship. This condition must be solved in an iterative way, as a sequence of solutions of the linearised condition. If this sequence converges, the result may be regarded as the solution of the non-linear condition.

It is assumed that the potential Φ may be analytically extrapolated from the deformed water surface $z=\zeta$ to the flat water surface $z=0$. Then the potential Φ may be developed into a Taylor series, taking into account only the linear terms. It corresponds to the assumption that the generated gravity waves have small amplitude in relation to their length. After some transformation a linearised boundary condition on the free water surface is constructed in the form:

$$\frac{\partial^2\Phi}{\partial x^2} - \frac{g}{V_s^2}\cdot\frac{\partial\Phi}{\partial z} = 0 \tag{7}$$

with the corresponding expression for the wave height:

$$\zeta = -\frac{V_s}{g}\cdot\frac{\partial\Phi}{\partial x}\Big|_{z=0} \tag{8}$$

The above relations are known from the theory of wave resistance of a ship in deep water.

The free water surface is divided into a number of elements, in the manner similar to the hull surface. Now the velocity induced in the control points on the free surface by the sources on the hull may be calculated. This calculation is analogical to that leading to evaluation of the matrix elements A_{ij} above. The entire previously accumulated information about geometry of the hull and free water surface is employed here. The velocity generated in the i-th point on the free water surface by the j-th source on the hull surface may be described as:

$$V_i = \sum V_{xij}\sigma_j \tag{9}$$

where: σ_j - sources on the hull, V_{ij} - induction factors matrix element.

The first step in calculation of the deformed free water surface consists of determination of the so called Bernoulli waves. These are obtained by solving the dynamic boundary condition requesting equilibrium of pressure on the water surface. The geometry of the Bernoulli wave system is described by the following relation:

$$\zeta_i = -\frac{V_s}{g}V_{xi}\Big|_{z=0} \tag{10}$$

It describes displacement of the water surface caused by the system of sources modelling the ship hull.

In the next step the system of Bernoulli waves is transformed into the system of waves generated by the moving ship. This is done by means of Green function for the moving pressure impulse. The formulae for deformation of the where: σ - is the source density, r - is the distance between point q where the source is located and point p(x,y,z) where the potential is determined, n_x - is the x component of a unit length vector normal to the surface element dS, V=Vs + Vip, Vs- ship velocity, Vip- velocity induced by the propeller(s). The velocity potential in the above form fulfils the Laplace equation and condition at infinity for an arbitrary function σ. Consequently, this function must be determined by the boundary condition on the hull.

The numerical solution starts with discretisation of the hull wetted surface, which is divided into a grid of flat, quadrilateral elements. Each quadrangle is described by the control point placed in its centre, unit length normal vector, surface area etc. It is assumed that the source intensity is constant over the element. Evaluation of the source intensity distribution on the hull surface is performed according to the method of Douglas-Neuman [1].
After discretisation of the surface S equation (5), which is the Fredholm equation of the second kind, is converted into a system of linear equations in the following form:

$$\sum_{j=1}^{N} A_{ij}\sigma_j = -n_{xi} \cdot (V_s + V_{ip}) \qquad (6)$$

where: n_{xi}- unit length normal vector, σ - source density on the i-th quadrangle, A_{ij}- induction matrix element, N - number of elements on the "double" hull.

Determination of the matrix elements is based on calculation of the velocity induced in the control point of the i-th quadrangle by the source of unit intensity located in the j-th quadrangle. This velocity is projected on the normal vector of the i-th quadrangle. The system of N linear equations (6) is solved using the Gauss elimination method. When the source distribution on the hull surface is known, the velocity and pressure in all control points may be calculated.

Alternatively, it is possible to include or exclude the velocity induced by the propeller(s). As a matter of fact, the effect of propeller is not very important in the potential flow calculation. The evaluation of the propeller induced velocity is performed using lifting surface theory. The lifting surface [4] is constructed for the whole propeller using 20 bound vortex elements for each blade. In order to fulfil the Kelvin theorem about conservation of vorticity a system of helical free vortex surfaces is introduced behind the blades. The solution is based on the kinematic boundary condition requesting no flow through the lifting surface and on the Kutta condition. The velocity induced by vortex elements is evaluated using Biot-Savart formula. Solution of the system of linear equations resulting from the boundary condition leads to the vorticity distribution on the blades. This enables calculation of the propeller induced velocity in the surrounding space and evaluation of the pressure distribution on the blades. The latter leads, after appropriate corrections for viscosity, to the control values of propeller thrust and torque. The velocity field induced by the propeller(s) is added to the hull induced velocity field and the combined field is

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free water surface due to the moving pressure impulse are taken from [2]. These formulae have been transformed and employed in a separate subroutine. Once the wave system is calculated, the magnitude of the wave resistance may be assessed, according to the following relation:

$$R_w = \frac{1}{2}\rho g \oint_{dS} \zeta \cdot |\zeta| dy - \frac{1}{2}\rho \int_S \left(\Phi_x^2 + \Phi_y^2 + \Phi_z^2\right) n_x dS + \rho \int_S \Phi_x \Phi_n dS \qquad (11)$$

where: S - wetted surface of the hull, n_X - x component of the unit length normal vector on the hull.

3 The computer system

On the basis of the above described theoretical background the computer system for determination of flow around the ship including the effect of free water surface and propeller(s) has been developed. The system includes several modules: four performing essential calculations and others responsible for graphical presentation of input data and results on VDU's, printers and plotters. The structure of the system enables using all program modules almost independently. The block diagram of the system is presented in Fig. 1.

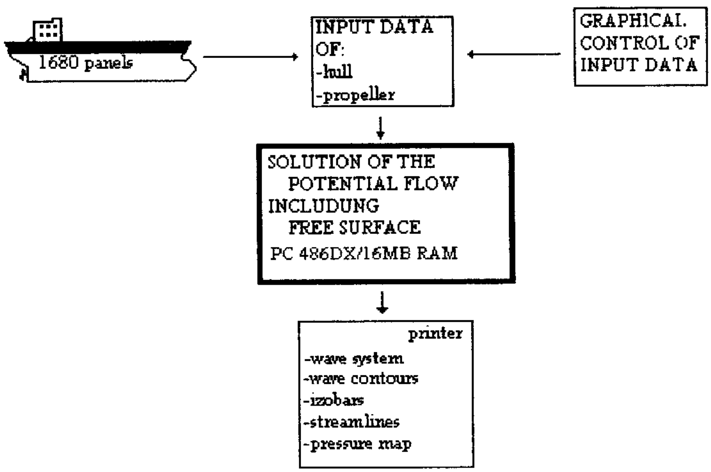

Fig. 1

The calculation procedure requires the ship hull to be described by a number of quadrilateral flat surface elements - panels. The distribution of panels depends on the detailed hull geometry. In general the hull may be divided into three zones having different degree of geometrical complication, namely: bow zone, midship zone and stern zone. After the input data describing hull geometry is introduced the midship zone is divided into panels automatically, while the bow and stern zones require some interaction with the user. Graphical presentation

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of the resulting division of the hull into panels enables easy correction and modification.
Currently used PC 486/50MHz/16Mb RAM computers allow for the maximum of 1680 panels on the hull wetted surface (60 elements along X axis with 28 elements along each frame). The region of the free water surface extending 0.5 L_{pp} forward of the bow, 1.0 L_{pp} aft of the stern and 3/8 L_{pp} to both sides from the plane of symmetry is divided into 4200 panels (140 elements along X axis with 30 elements in the transverse direction).

The calculation supplies the following information: streamlines on the hull surface, static pressure distribution on the hull, wave profile along the waterline, wave system on the free surface and value of the wave resistance.

4 Calculation examples and discussion of the results

For the purpose of system presentation the calculations have been performed for the Wigley hull (W) and a modern container ship (C).

The Wigley hull has simple parabolic shape described by the following equation:

$$y = (L/20)\{1 - (2x/L)^2\}\{1 - (z/0.0625)^2\} \qquad (12)$$

In calculation the values L=2.5m, B=0.25m and T=0.1563m were taken. Fig. 2 shows the wave system for the Wigley hull at Froude number Fn = 0.25. Apart from that the calculations of streamlines, wave systems and pressure distribution on the Wigley hull were performed for a wide range of Froude numbers. The calculated results agree quite well with the experimental data taken from [3].

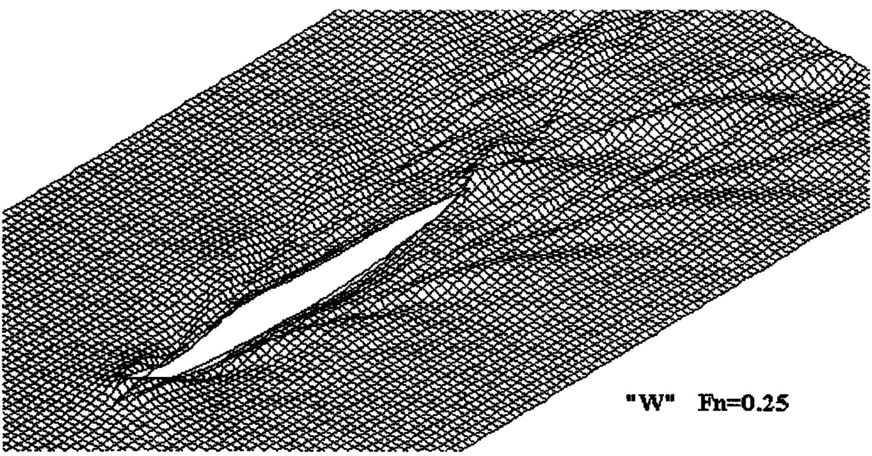

Fig. 2

The container ship "C" has the following parameters: Lpp=165.2m, B=26.5m, T=9.0m and moves with the velocity V=10.76m/s.

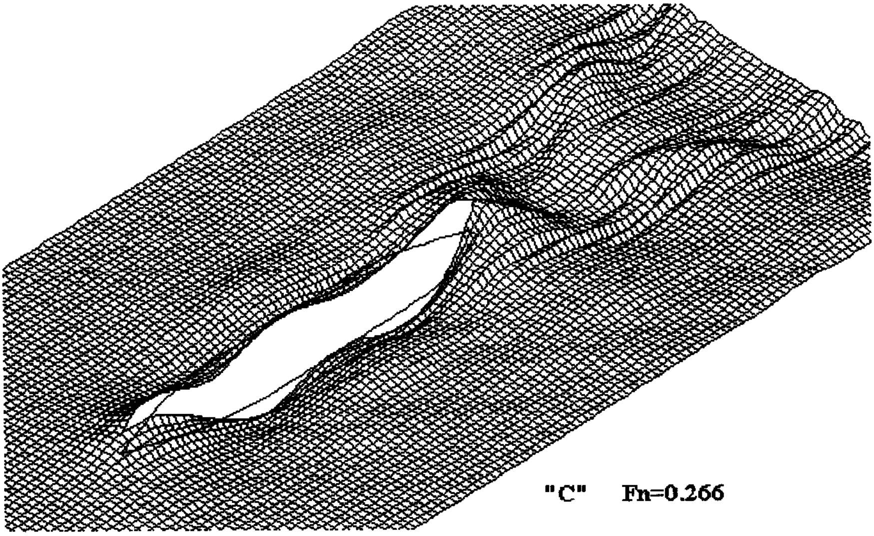

Fig. 3

Fig. 3 shows the calculated wave pattern while Fig. 4 presents the lines of constant wave elevation for the container ship in the above condition.

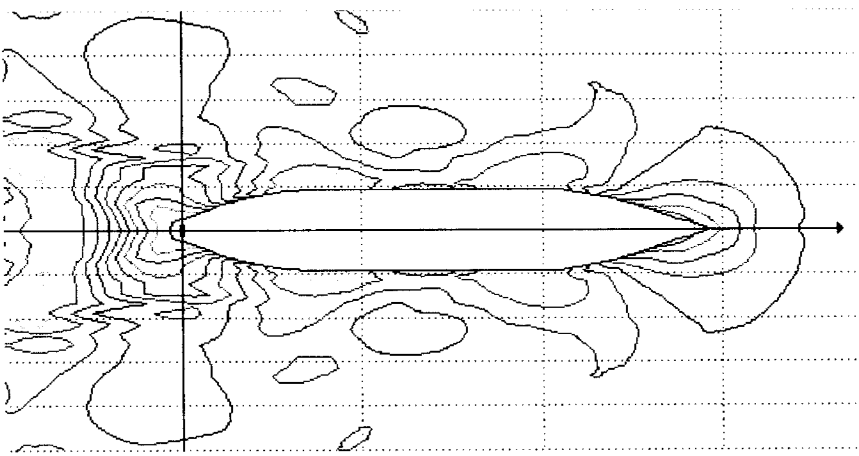

Fig. 4

In general the comparison of calculated and experimental results demonstrates good agreement. The differences in wave height in the stern region are due to the viscosity effects, which are neglected in potential flow calculation.

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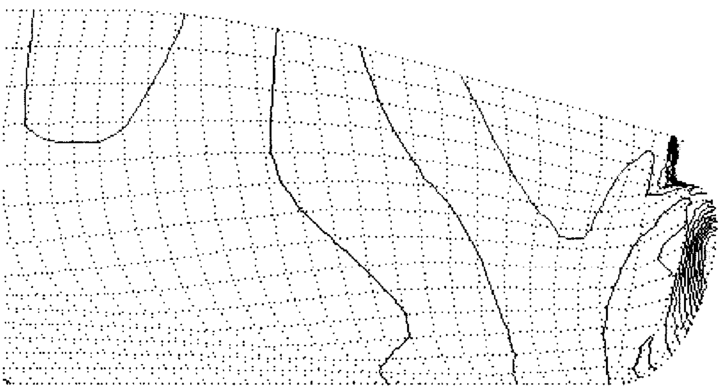

Fig. 5 shows the pressure distribution in the form of isobars on the bow section of the ship "C".

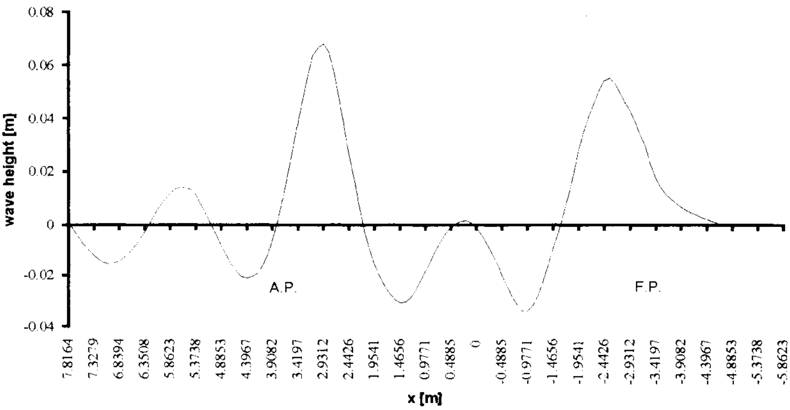

Fig. 6 presents wave profile along the waterline for the ship "C".

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