Underlying mathematical methods used in the Software family Autowing

(short information)

1.Wingship aerodynamics.

The mathematical model is based on the Vortex Lattice Method (VLM). The modified steady and unsteady VLM is applied in the Code Autowing Release 1.0,1.1, 2.2 and 2.3.Proposed version of the VLM method has several distinguished features listed below:

- First feature relates to the calculation of unsteady derivatives (harmonic oscillations)(Autowing Release 1.0). In this method, the boundary conditions are satisfied at every moment of time upon real instantaneous position of lifting elements, whereas in traditional approaches no-through conditions are satisfied on a averaged position of lifting elements. Account for orientation of lifting surface with respect to the ground is the first and the main source of nonlinearity of aerodynamic characteristics of ekranoplans. Importance of this factor is discussed in Ref. [1].
- Secondly the method is generalized for account of nonlinearity due to deformation of vortex wake and wind-wave perturbations (Autowing Release 1.0). A special iterative technique called the method of mean approximation is suggested. The method proved to be efficient, accurate and applicable to engineering (see Refs. [1] and [2]).
- Work [1] gives examples of application of this method for lifting systems with harmonically changing area which is a practical problem for unsteady motions of wingship with partially submersed lifting surface (Autowing Release 1.1). To derive the governing equations we used the Lagrangian coordinates connected with the lifting surface. In these coordinates, the harmonically changing area is kept constant in time. The governing equations are sufficiently simplified.
- A special investigations, based on the formulation of the boundary layer theory and the viscous/inviscid interaction algorithm, had been performed to account for the viscous effects. Results of calculations demonstrated a strong influence of the viscosity on the statical longitudinal stability of wingships (Autowing Release 2.2).

The method had been extensively applied to calculation of real configurations of ekranoplans and from this viewpoint is sufficiently probated. Synopsis of long-term calculations of the well-known soviet wingships Orlyonok, Lun, SKB, MPE and Ela01 is presented in [1].

2. Hydrofoil hydrodynamics (Autowing Release 2.2 and 2.3).

The novel computational vortex method is used to solve this problem. We consider a hydrofoil of arbitrary wing configuration advancing at constant forward speed V in an incompressible, inviscid and irrotational fluid domain. The x-axis of Cartesian frame fixed with the hydrofoil points to the direction of the direction of the hydrofoil forward velocity, and y-axis is positive upward. To simulate the nonlinear free surface waves we use the method of integral equation derived by distributing the vortex sheet of unknown vector density $\vec{\gamma}$ on the free wave surface. The vector $\vec{\gamma}$ can be obtained from the dynamic boundary condition

$$VW_x - \frac{1}{2}\left|\vec{W}\right|^2 - gy = 0 \qquad (1)$$

where $\vec{W}$ is the velocity under the free surface, g is gravity and y is the wave elevation. Without loss of generality we can decompose the vector $\vec{\gamma}$ at each point of the computational domain as the sum of two components lying in the plane which is tangential to the free surface. The first component γ_ς is assumed to be laid in the plane which is perpendicular to the x-axis and another one γ_ξ is perpendicular γ_ς . After some transformations we have from (1):

$$\gamma_\varsigma = \left|\vec{W}_0\right|^2 + (\vec{n} \times \vec{\gamma})\vec{W}_0 + \frac{1}{4}\left|\gamma\right|^2 + 2\frac{y}{Fn^2} - 2W_{0x} \qquad (2)$$

Together with the divergence-free condition $\nabla \times \vec{\gamma} = 0$ and conditions at infinity the equation (2) represents a closed system of governing equations for the vector density . The velocity can be calculated using Biot-Savart's law. In the numerical implementation the free surface is truncated at x_0 and x_1, and at z_0 and z_1 . The surface vorticity $\vec{\gamma}$ is represented as a number of closed discrete vortex frames (the vortex lattice method). In this case the divergence-free condition is satisfied automatically. The kinematic condition on the free surface is used to calculate the form of the free surface. It is assumed that

$$\vec{\gamma}(x = x_0) = 0, \qquad \vec{\gamma}(z = z_0) = 0, \qquad \vec{\gamma}(z = z_1) = 0,$$
$$y(x = x_0) = 0, \qquad y(z = z_0) = 0, \qquad y(z = z_1) = 0.$$

The lift-force acting on hydrofoils is introduced as a distribution of vortices on the surface of mean lines for each lifting element. The vortex distribution is organized as a number of horseshoe-shaped discrete vortices. The legs of the vortices continue in the trailing wake. The strength of the vortices in the wake is kept constant. The strength of the bound vortices is determined from the non-through boundary conditions at discrete control points lying in the centers of panels. The unknown form of the vortex wake is determined from the streamline equation according to the Nonlinear Vortex Lattice Method (NVLM). The viscosity is taken into account using an iterative procedure based on the viscous-inviscid flow interaction theory.

The present full nonlinear Boundary Element Method has to be treated iteratively. Further details about the method and algorithm are given in [2] and [3]. A set of tests which examines the accuracy of the method for prediction of the wave elevation behind a hydrofoil, was performed for various wing systems. The numerical calculations of wave elevation obtained using this method are in a good agreement with experimental data obtained in the Krylov Institute and the Central Hydro-Aerodynamic Institute. A good agreement with measurement was also reached for the lift coefficient of hydrofoils at different Froude numbers Fn > 1 and depths of submergence. The method and the software were sufficiently aprobated for the calculation of the high-speed ship Autojet [4]. The wing configuration of the Autojet consists of a forward hydrofoil and planing hull moving in the vortex-wave wake of the hydrofoil. It is shown that the nonlinear terms in the boundary conditions on the free surface need to be accounted for in practical calculations of the interaction between forward and back wing systems of the fast ships.

3. Planing surface including planing surface with a stepped bottom hydrodynamics (Release 2.2 and 2.3).

We use a Vortex-Lattice Method and so-called wing-similarity proposed first by Wagner to calculate a planing surface. The wetted area of the planing surface is determined iteratively using Wagner-Sheglova (see, for instance, [5]) method. It is assumed that the planing surface is moving in the vortex-wave wake generated by a foregoing hydrofoil. To calculate a planing surface in the vortex-wave of a hydrofoil, this software and the software intended for calculations of hydrofoils are integrated in the software package Autowing.

The planing surface with stepped bottom is considered as a set of planing surfaces each of each is moving in a wake of a foregoing planing surface. The nonlinear wake after a planing surface is calculated using the method described in the section 2. Hydrodynamics of each step is calculated by the Vortex-Lattice Method. The influence of spoilers located on the trailing edge of a planing surface is calculated using the empirical formulae proposed by Bannikov and Lukashevsky [6].

The applied methods don’t enforce any serious limitations to the geometry of planing surfaces.

4. Attitude and dynamics of a high-speed ship.

Securing enhanced hydro-aerodynamic efficiency for high-speed ships both in take-off regime and in cruise should not be detached from consideration of matters of the vehicle's attitude and dynamics. The Software Autowing 2.3 treats issues of ships attitude and dynamics on the basis of general equations of motion of the vehicle. The Autowing 2.3 allows to investigate nonlinear dynamics and stability of the hydrofoils, planing ships and combination of a hydrofoil and a planing surface moving on a calm sea.

5. Design of wing sections of high-speed ships (only in Autofoil extension).

The mathematical model of this software has already been tested in Russian wingship and hydrofoil industry. Essentially, the method of profile design with a given velocity (or pressure distribution) is as follows (Pavlovets(1971)). A stream function is assumed to be consisting of two terms:

$$\Psi = V_\infty \cdot (-x \cdot \sin\alpha + y \cdot \cos\alpha) + \frac{1}{2 \cdot \pi} \cdot \oint_L V(s) \cdot \ln\sqrt{(y(s_0) - y(s))^2 + (x(s_0) - x(s))^2}\, ds \quad (1)$$

The first term is the stream function of upstream, the second one describes the stream function of the vortex sheet modelling hydrodynamic influence of a wing section. Because the stream function is kept constant along the profile contour , we obtain from (1):

$$y(s_0)=\Psi\Big|_{trailing\quad edge}+V_\infty\cdot x\cdot\tan\alpha-\frac{1}{2\cdot\pi\cos\alpha}\cdot\oint_L V(s)\cdot\ln\sqrt{(y(s_0)-y(s))^2+(x(s_0)-x(s))^2}\,ds \qquad (2)$$

The value of the stream function on the trailing edge $\Psi\Big|_{trailing\quad edge}$ is obtained from (1). The unknown contour of wing section with a given velocity distribution $V(s)$ is calculated from the Eq. (2) which is solved iteratively.

6. Hydrofoil Assisted Catamarans

See [8].

References

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