Numerical Computation of the Flow Around Surface-piercing Wings and Hydrofoils Close to a Free-surface

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Introduction

The performance of many hull types is highly dependent on the hydrodynamic properties of their keels, rudders and hydrofoils. A numerical prediction for these cases includes two major difficulties: the presence of a free water surface and the vortex system generated by the lifting parts of the hull. A three-dimensional panel method for the simultaneous prediction of free-surface waves, lift and induced drag is used to study the interaction between the free-surface and surface-piercing wings and hydrofoils.

The linear Rankine source method presented in (Kim, K. J. 1989) is extended to take lift and induced drag into account. The lift-force acting on the surface-piercing wing and hydrofoil is introduced as a distribution of dipoles on the lifting surface (Hess, J. L. 1972). The dipole distribution is in the spanwise direction organized as a number of strips. Each strip starts at the trailing edge of the section profile and continues towards the leading edge and back to the trailing edge on the opposite side of the profile. The strip then continues in the trailing wake. The dipole strength is zero at the starting point of the strip and increases linearly around the profile. The dipole strength is kept constant as the strip continues into the trailing wake. A constant dipole distribution is assumed in the spanwise direction on each strip. This gives a step variation of the dipole strength in the spanwise direction of the wing. One Kutta-condition is introduced for each strip to determine the strength of the dipole distribution. The Kutta-condition is introduced as a flow-tangency condition where the flow is forced to leave in a specified direction downstream of the trailing edge. A source/sink distribution is also used in addition to the dipole distribution both on non-lifting and lifting surfaces. A Trefftz-plane integration technique is used to compute the lift and induced drag from the lifting surface. The Trefftz-plane integration is known to give more accurate values of the drag than the pressure integration method.

Different levels of approximation can be used for the free-surface. The most simple one is the double-model solution where the free-surface is treated as a symmetry plane. If the interaction between the free-surface and the vortex-system of a lifting surface is to be included in the analysis, a more accurate representation of the free-surface is needed. A first step is then to linearize the free-surface boundary conditions with respect to a basic-model (zero Froude number) solution and apply the linearized free-surface boundary conditions on the undisturbed free-surface. An even higher accuracy can be achieved if the free-surface boundary conditions are applied on the initially unknown wavy free-surface. This leads to a non-linear method and has to be treated iteratively. A linear method is here used for the free-surface boundary conditions.

The basic-model (zero Froude number) solution is in the present method computed as a double-model solution where a symmetry condition is used at the undisturbed free-surface level both for lifting and non-lifting surfaces. In particular for a surface-piercing wing the double-model solution gives a spanwise bound vortex distribution that is symmetric with respect to the undisturbed free-surface. This implies that there will be no concentrated vortex at the symmetry plane. The double-model image of the surface-piercing wing is included also when the linearized free-surface problem is formulated which excludes a vortex at the undisturbed free-surface also for the free-surface problem.

Surface-piercing wing

The influence of the free-surface on the lift force produced by sailing yacht keels is discussed in (Sloof, J. W. 1984) and the free-surface effects on a yawed surface-piercing plate are presented in (Maniar, H., Newman, J. N., Xu, H. 1990). The free-surface effects of surface piercing bodies are studied both by computations and experiments in (Ba, M., Coirier, J., Guilbaud, M. 1992). From these references it is clear that the free-surface has a strong effect on the lift-force produced by a surface-piercing body.

The free-surface effects for a surface-piercing wing in the speed-range Fn = 0.3 to 1.3 is investigated for a wing of aspect ratio 2 (wetted part) using the NACA 63_2A015 profile. The angle of attack is 6 degrees for all speeds. The vortex distribution close to the free-surface shows an interesting dependence of the Froude number. When the speed is increased from zero where the free-surface acts as a symmetry plane the vortex strength is increased up to a maximum for a Froude number of approximately 0.5. The vortex strength then decreases when the speed is increased further and the vortex distribution becomes similar to the wing of aspect ratio 2 and to the distribution for the infinite Froude number limit. The behaviour for the higher Froude numbers was expected but the increase of the vorticity at low speeds was not expected, and it is a question whether this is a real physical effect or if it is a result of the assumptions included in the formulation of the linear method. The increase of the lift-force coefficient to a maximum is shown experimentally and by computations in (Ba, M., Coirier, J., Guilbaud, M. 1992), and it is therefore believed that this is a real physical effect but it may be overestimated due to the assumptions in the linear method. The part of the wing between the undisturbed free-surface and the wave trough is included in the computation while the part of the wing covered by the wave crest is missing. It is obvious that the solution for the uppermost part of the wing is questionable since the wave trough on the suction side is about 10% of the span at Fn = 0.5. The increase of the vortex-strength is however not only a local effect close to the free-surface but can be seen further down.

One explanation to this effect may be found by studying the wave profiles and pressure distributions on both sides of the wing. The deep wave trough on the suction side gives a low pressure region. The magnitude of the pressure disturbance is large close to the undisturbed free-surface. It then decays further down. On the pressure side of the wing there is a wave crest from the leading edge to the mid-chord creating an increased pressure and then a wave trough creating a lower pressure towards the trailing edge. The net effect will be an increase of the lift-force due to the pressure disturbance from the free-surface waves which means an increased vortex strength. The pressure disturbance is also present at higher Froude numbers but it is much smaller.

The angle of attack was also varied for the different Froude numbers. The slope of the lift coefficient curves increases to a maximum at about Fn = 0.5 and then decreases towards a minimum at higher Froude numbers. This minimum should correspond to the infinite Froude number limit. The drag coefficient also shows a maximum at about Fn = 0.5. The wave resistance is included both in the lift and drag coefficients.

An interesting phenomenon was detected during the computations. Above some value of the Froude number there seems to be a jump in wave height at the trailing edge. For Froude numbers below 0.5 this jump does not occur for the computed angles of attack. But for Froude numbers above 0.7 the jump occurs for all angles of attack above zero. The jump appears as the wave trough on the suction side of the profile reaches the trailing edge of the wing. This phenomenon is discussed in (Maniar, H., Newman, J. N., Xu, H. 1990) for a flat plate and is verified by experiments where a critical Froude number for this effect was found. The experiments show large transverse velocities at the trailing edge which means that the Kutta condition is not satisfied for speeds above the critical Froude number. In a potential flow calculation this jump should not occur because the Kutta condition and the free-surface boundary condition do not allow for this jump. The jump appears anyhow in the present calculation and the reason for this is probably that the Kutta-condition is only satisfied at discrete points at the trailing edge and that the free-surface boundary condition is applied at the undisturbed free-surface half a panel width aside of the trailing edge.

A double-model image of the surface-piercing wing was included in the formulation of the free-surface problem above and it is a question if this gives the right representation of the vortex distribution close to the free-surface since a symmetry condition is enforced. The free-surface problem may also be formulated as a single-model problem where the image of the surface-piercing wing is excluded both in the basic-model (zero Froude number) solution and when the free-surface problem is formulated. The single-model solution for the basic-model (zero Froude number) requires a panelization of the free-surface together with a Neuman condition on the free-surface panels. The single-model gives only an approximate zero Froude number solution since the Neuman condition applied on the discretized free-surface gives an approximate rigid wall. In this case the singularities on the free-surface have to carry the image effect of the lifting and non-lifting surfaces. The single-model formulation of the surface-piercing wing gives a vortex at the free-surface since the bound vorticity must drop to zero at the free-surface and a step distribution of vorticity is used in the spanwise direction. The potential flow formulation of the free-surface does however not allow for a concentrated vortex at the free-surface since the pressure must be finite. The appearance of the vortex in the computations is probably due to the application of the Kutta-condition and the free-surface boundary condition as explained above for the wave height jump. The vortex on the free-surface will create computational problems behind the trailing edge if the free-surface panel distribution is refined close to the position of the vortex. These problems are avoided if a double-model formulation is used. From a computational point of view the double-model formulation therefore seems to better than the single-model formulation but it is still not clear which of the two formulations that give the best representation of a real flow situation.

Hydrofoil

The interaction between a free-surface and the vortex-system created by a hydrofoil was investigated using the NACA 63_2A015 profile for a hydrofoil of aspect ratio 4. Three series of computations were carried out for the hydrofoil. The first investigates the influence of the distance to the free-surface, the second is a variation of the angle of attack, and the last shows the influence of the Froude number.

The hydrofoil was computed for three draughts, 1.0, 0.75 and 0.5 chord lengths below the free-surface. In all three cases an angle of attack of 6.0 degrees was used and the Froude number was 0.4. A very strong interaction between the hydrofoil and the free-surface can be seen for the draught 0.5 chord lengths. The influence of the free-surface then decreases rapidly as the draught is increased and the influence of the free-surface is small already at 1.0 chord lengths below the free-surface. The waves created for the draught 0.5 chord lengths are very steep and wave breaking would most certainly occur in a real flow situation.

A variation of the angle of attack was carried out for the Froude number 0.4 at the draught 0.5 chord lengths. The angle was varied from 0 to 10 degrees plus an additional angle of -6.0 degrees. A lift-force produced by the blockage effect of the free-surface at zero degrees can be determined. It is also interesting to note the difference in absolute values of the vortex strength for 6.0 and -6.0 degrees. The computations shows a strong interaction between the free-surface and the vortex-system of the hydrofoil. The reversed direction of the bound and trailing vortices together with the change of pressure on the hydrofoil when the angle of attack is changed from 6.0 to -6.0 degrees creates wave patterns that are completely different both in amplitude and shape downstream of the hydrofoil. The positive angle creates a converging wave system while the wave system from the negative angle shows a more divergent behaviour compared to the zero angle of attack. The zero angle of attack creates waves that are on the limit for wave breaking. Positive angles gives larger wave amplitudes while the negative angle gives smaller amplitude.

A Froude number variation was also carried out for the draught 0.5 chord lengths and 6.0 degrees angle of attack. The Froude number was varied from 0.3 to 0.9. The spanwise vortex distribution and the lift and drag coefficients show that the effect of the free-surface is to increase the lift-force for Froude numbers up to about 0.4. The lift-force is then diminished as the speed is increased. The analysis carried out in (Piperni, P. 1987) shows a similar behaviour for two-dimensional hydrofoils.

References

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DISCUSSION

Nakatake: According to our experience, the flow tangency condition is not enough for the Kutta condition for 3-dD wing problem. Did you check the pressure distribution on wing surface to confirm the equal pressure condition? Please explain about the Trefftz-plane integration technique.

Janson: Thank you for the comment on the flow tangency condition. In our method the flow is forced to be tangent to the bisector of the trailing edge on each of the strips in the spanwise direction and the condition is applied at the bisector 0.005 chord lengths downstream of the trailing edge. This implementation is an approximation of a real flow situation at the trailing edge and it does not explicitly enforce any condition on the pressure at the control points of the panels upstream of the trailing edge. The control points of the panels at the trailing edge were in the computations presented at the Workshop located 0.0125 chord lengths upstream of the edge and different pressures did occur at the two sides. One of the surface-piercing wing cases is now re-computed using a much smaller panel size upstream of the trailing edge. The pressure difference is then reduced but it is still present.

The lift force and induced drag due to lift is in the present method calculated by a far-field integration technique described in [1] and [2]. The lift force L and the induced drag D are derived from the momentum flux and the kinetic energy respectively and the final expressions include an integration of the trailing vortex system at a plane far downstream, the Trefftz-plane, see figure 1. The lift force is written

$$L = \rho \cdot U \cdot \int_{-0.5s}^{0.5s} \Gamma(y)\, dy$$

and the induced drag is obtained from

$$D = -\frac{\rho}{2} \int_{-0.5s}^{0.5s} \Gamma(y) w(y)\, dy$$

where the integration is over the span of the trailing wake at the Trefftz-plane and Γ is the spanwise variation of vorticity, w is the downwash at the Trefftz-plane computed from the Biot-Savart law.

$$w(y) = \frac{1}{2\pi} \int_{-0.5s}^{0.5s} \frac{\partial}{\partial y}\Gamma(y)\frac{1}{y - y_0}\, dy$$

[1] Greeley, D.S., Cross-Whither, J.H. (1989), *Design and hydrodynamic performance of sailboat keels*, Marine Technology and SNAME News, Vol. 26/4

[2] Newman, J.N. (1977), Marine Hydrodynamics, The MIT press, Cambridge, MA

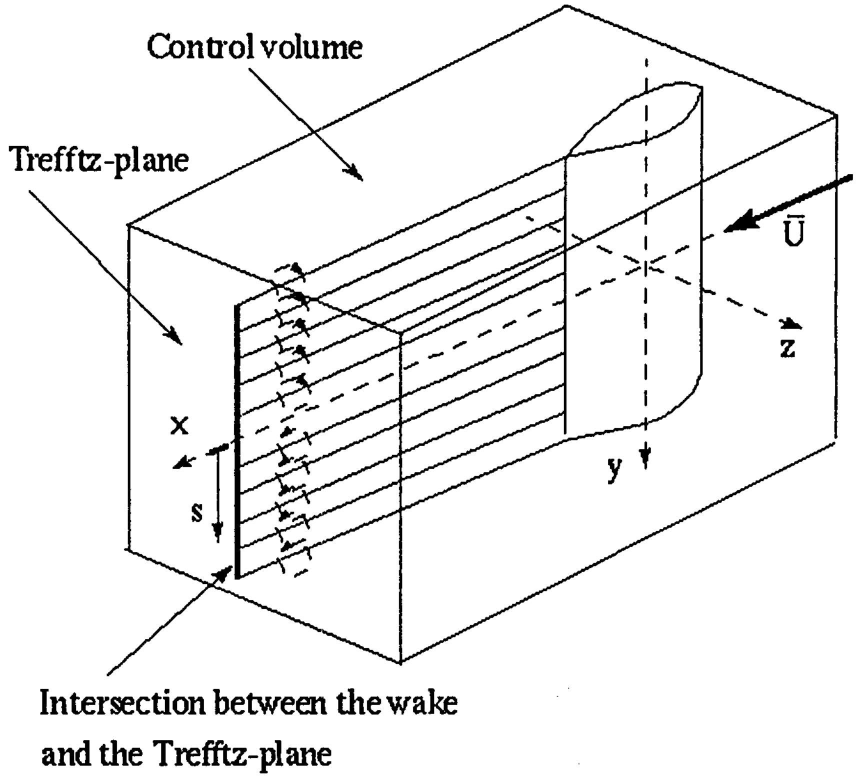

Figure 1: Trefftz-plane integration