NUMERICAL INVESTIGATION OF THE FLOW AROUND WING TIPS

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Abstract: The paper dwells with the problems of modelling of flow around wing tip and tip vortex cavitation. Theoretical bases of vorticity method and vorticity calculation models for design and estimation of hydrodynamic characteristics of the hydrofoil are presented. Basic assumptions of double layer lifting surface model are described. Double layer lifting surface model enables proper modelling of the phenomena occurring in the flow around a hydrofoil tip and especially generation of free vortices system.

Keywords: vortex theory, lifting surface model, hydrofoil

1. Introduction

The methods based on Navier-Stokes equation have been dominating in Computational Fluid Dynamics (CFD) for a few years. Nevertheless, there exist many problems, especially within fluid flow machinery, which deal with three-dimensional flows with circulation, in which a vortex surface spreads into infinity behind a body and consequently the flow domain became a multiply connected region.

A theorem that states that the solution of such a flow is unambiguous [3] can be expressed as follows: "the solution to the Neumann exterior problem in a doubly connected region is uniquely determined (up to an additive constant) only when the circulation is specified. For the same boundary and infinity conditions, different values of the circulation yield different solution". The theorem has been formulated for non-viscid fluid but is also valid in the viscous flow case.

What does it mean?

For such flow cases the first stage of calculations should consist of the determination of circulation around a body and especially in the flow behind it. Navier-Stokes based approach can be applied in succeeding steps of calculation. The knowledge of the shape and intensity of vortex surfaces is necessary for the formulation of boundary conditions for Navier-Stokes equations.

It happens relatively often that the second step of calculations is unnecessary. For example in case of screw propellers (neglecting conditions that are extremely different from design ones) the lifting force connected with circulation on blades is five times greater than the drag force connected with viscosity. In such cases even significant discrepancy in drag estimation influences insignificantly the prediction of total force generated on a blade. Similar situation can be met while considering the flow around a hydrofoil, through a water turbine, fan pump, etc.

Moreover, the investigation of the flow around the wing tip can be rated among the problems that can be solved basing on the determination of vorticity field around the wing.

2. Theoretical background of the vortex method

It is advisable to introduce the vorticity $\vec{\Omega}$ while analysing the movement of incompressible fluid:

$$\vec{\Omega} = rot\vec{V}, \tag{2.1}$$

where $\vec{V}$ denotes fluid velocity.

By acting with the rotation operator on both sides of Navier-Stokes equation pressure can be eliminated and a time dependent equation for liquid vorticity can be obtained:

$$\frac{\partial\vec{\Omega}}{\partial t} + rot(\vec{\Omega}\times\vec{V}) = \nu\Delta\vec{\Omega}, \tag{2.2}$$

where ν is a fluid kinematic viscosity.

The molecular diffusion component $\nu\Delta\vec{\Omega}$ can play a significant role only in locations of intense vortex concentration [1], for example during the creation of concentrated forms of free vorticity. Within the regions in which no such concentration is predicted molecular diffusion component can be neglected and consequently a Helmholtz equation is obtained:

$$\frac{d\vec{\Omega}}{dt} - (\vec{\Omega}\cdot\nabla)\vec{V} = 0. \tag{2.3}$$

Basing on the combination of this equation with Stokes theorem:

$$\oint_l \vec{V}d\vec{l} = \int_S \vec{n}\, rot\vec{V}\, ds, \tag{2.4}$$

a series of theorems concerning vorticity fields can be obtained. These theorems form a theoretical basis for creation of vortex models enabling the numerical estimation of velocity field in the flow around an arbitrary body.

Generally speaking, the creation of a vortex model of the flow around a specific body consists in the determination of the vorticity distribution substituting the presence of the body in a liquid and a vortex trace behind it.

Time and space dependent vorticity distribution serves as the source for calculation of induced velocity field. In this case separate vortex filaments represent the vorticity:

$$\bar{\Omega}(\vec{r})\,d\tau = \Gamma\,d\vec{l}\,, \tag{2.5}$$

where: $d\tau$ — specified volume containing vortex filament,

Γ — velocity circulation,

$d\vec{l}$ — directed element of vortex filament.

A velocity field can be determined with the use of Biot-Savart theorem, which is crucial in theory of flow:

$$\vec{V} = \frac{\Gamma}{4\pi}\int_{l}\frac{d\vec{l}\times\vec{R}}{R^3}, \tag{2.6}$$

where $\vec{R}$ denotes a vector connecting vortex element and control point.

3. Vorticity models

Vortex calculation models have been created for design and determination of characteristics of hydrofoils, including screw propeller blades. The statement that vorticity is concentrated within a thin layer spreading over both sides of a hydrofoil serves as the basic assumption. In the past when sufficiently fast computers were not available calculation model had to be significantly simplified. A single layer lifting surface model of the propeller blade has been applied successfully for many years.

The first step of such a calculation model consists in decomposition of the force acting on a blade into two components – lifting force depending on circulation and friction drag force. The set of vortices is related only to the lifting force. Drag force is estimated as a rule basing on hydrofoils model tests.

In a single layer lifting surface calculation model the vorticity is distributed on the surface created by the foil sections mean lines.

Such calculation models provide very good results as far as global force generated on a wing is concerned. In case of screw propellers the thrust and the torque can be estimated with 0.5% accuracy in design conditions. Moreover, the pressure distribution on blades, serving as data for cavitation phenomena prediction, indicates a good agreement with experiment almost on the whole surface of the blade. The only region of the blade, which cannot be properly modelled by single lifting surface model, is the tip region. The occurrence of vortex cavitation takes place in the hydrofoil tip region. Therefore, in order to describe that phenomenon adequately, a double layer lifting surface model was created. The basic assumption of double layer model is that the vorticity is distributed on both sides of the hydrofoil and with this assumption the model is approaching closer to the reality.

4. Double lifting surface model

Fundamental assumptions concerning double lifting surface model were formulated in 1979 [4]. Nevertheless, the numerical application of this model met certain problems, which had to be solved one by one in order to obtain the final solution. They were solved with the help of few hypotheses. Temporary hypotheses were formulated and applied during the creation of calculation algorithm. The acceptance of these hypotheses was carried out on the base of experimental verification.

The most important hypotheses concerned:

a) the choice of the position of the point where the extreme outer vortex filament sheds from the suction side of the wing,

b) the choice of the limit value of the normal component of the velocity along the vortex line from which the shedding of the vortex line from the foil surface takes place instead of modification of vorticity distribution,

c) determination of conditions of vortex filaments shedding from pressure side across the tip edge.

The system of the bounded vortices distributed appropriately and independently on the pressure and suction side of the wing complemented with the system of free vortices serve as the starting point for determination of the system of free vortices

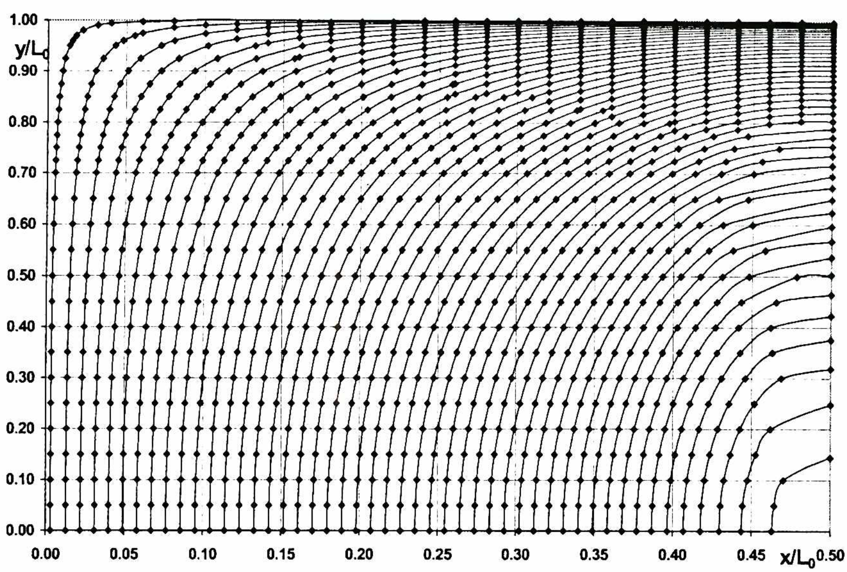

Figure 1. *Vorticity distribution on a wing surface*

from which tip vortices develop. In case of foils free vortices attain the form of rays and in case of screw propeller blades they attain the form of helical lines.

The initial distribution of lifting vorticity on the wing surface (Figure 1) can be obtained twofold (it is assumed that the shape and the foil cross section thickness distribution are known in both cases):

a) it is assumed that the magnitude and distribution of the lifting vorticity along the foil chord is known both on the suction and pressure sides. Mean lines and angles of attack are determined assuming that the vortices system is free from deformation,

b) a complete shape of the wing is assumed and then basing on the single lifting surface model a lifting vorticity is determined. Lifting vorticity is then divided between suction and pressure side due to a certain criterion.

The first step of calculations consists in determination of induced velocities in the points corresponding to the vortex elements. Huge induced velocities appear on the external vortex filaments for typical distributions of vorticity. Assuming a certain time step (adjusted by maximum value of induced velocity) the detachment of the extreme vortex on the suction side (possibly on the pressure side too) is determined. Figure 2 presents the normal component of the velocity in the location of the origin of vortex elements for few vortex filaments located on the suction side in the second step of calculation, after the detachment of the extreme filament. Huge magnitude of the normal velocity can be noticed in the location of the second filament. The detachment point of successive vortex filaments and location of free vortex filament are determined by appropriate assumption concerning the limit value of the velocity (hypothesis b).

The next step of calculation consists in the determination of the variation of the vorticity distributed on the wing caused by the vortex detachment and then the compensating vorticity in the location of the vortex detachment. The modification of

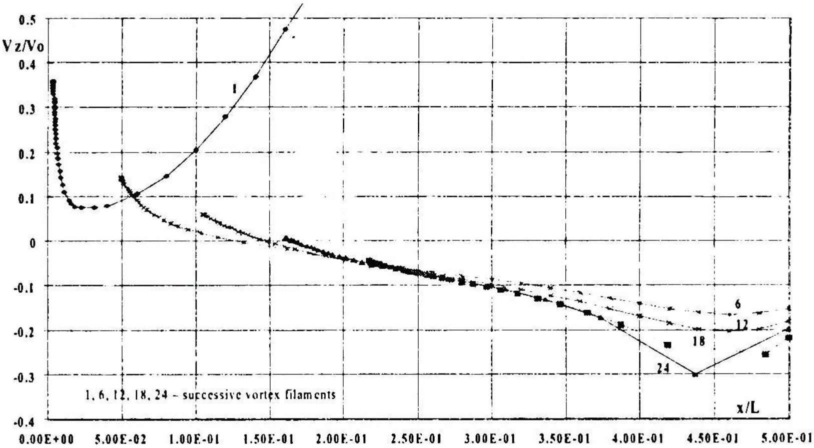

Figure 2. Normal component of induced velocity

shape of vortices both on the suction and pressure sides as well as the magnitude of compensating vorticity in the location of bound vortices detachment are both based on the condition of non-penetrability (Neumann's condition).

Usually the changes of vortices near the tip of the wing do not influence the magnitude of vorticity in the middle of the wing (where the vorticity gains its maximum). Therefore the modification of the shape of vortex elements does not require the change of their number as well as their intensity. In each moment of calculation it is also important to determine the detachment points of vortices from the pressure side across the tip edge (hypothesis c).

Correct choice of all three described above hypotheses requires the comparison between calculation and experimental results. Such a comparison and analysis was executed. The measurements of velocity and vorticity field in the flow around wing tip were carried on. The obtained results proved that the calculation model for vortex cavitation has been chosen correctly.

5. Results of calculations

The obtained results enabled to make a new step forward on the way of description of vortex cavitation and related phenomena. The most important revealing statement concerns the location of the regions of vortex cavitation inception in a blade neighborhood.

Basing on the analysis of the velocity and pressure fields around the wing, performed with the use of the described calculation model it can be stated that the conditions necessary for vortex cavitation inception (the existence of the flow region in which the pressure drops beyond the critical value and thus the rapid growth of cavitation nuclei is enabled) can be met only in the initial region of free vortex deformation. For typical shapes of screw propeller blade and typical load distributions two such regions can be distinguished.

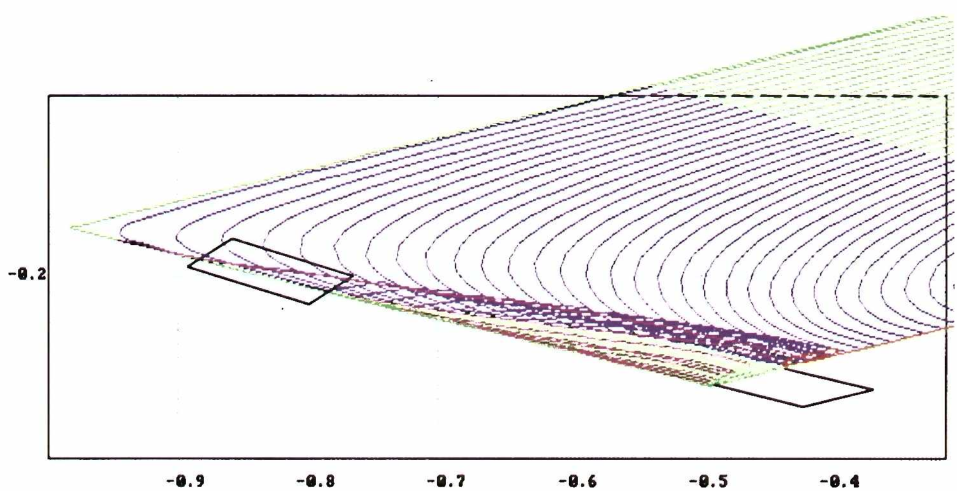

Figure 3. Regions of possible cavitation inception

These regions are presented in Figure 3:

region 1 — located above the surface of the suction side, close to the leading edge where the deformation of free vortices detaching form the suction side and partially from the pressure side begins,

region 2 — just behind the trailing edge where the deformation of the vortices detaching from the pressure side begins.

The above statement arises from the analysis of the pressure field around the blade tip with deformation of the system of free vortices taken into account. Studying the pressure field around the blade surface and around the deforming system of free vortices it can be noticed that in the initial phase of deformation of the free vortices system detaching from the blade surface a small region with a considerable concentration of vorticity appears. A considerable pressure drop appears around that region (see Figure 4a). Further deformation of vortices consists in helical rolling up of the next part of the free vortex surface. It causes the increase of the region of pressure drop but simultaneously the regions of considerable pressure drop disappear (see Figure 4b). This is a very important statement.

It indicates that there exists only considerably small region that serve as „factory of cavitation bubbles" and in which a rapid growth of gas microbubbles takes place. Afterwards these „grown up" bubbles enter the region with higher pressure and consequently a rapid decrease of their volume (implosion) occurs. This process is the source of the noise induced by vortex cavitation. The volumes of cavitation bubbles do not revert to the previous values what is caused by the difference between times of gas migration in two opposite directions: from water into the bubble and inversely.

The decreased but still with significant volume bubbles move downstream within a specific velocity and pressure field which occurs in the region of deforming free vortices. They join each other and form tip vortex with cavitating core which is characteristic for that type of cavitation.

The cavitation core of such vortex (or vortices) responds to the changes of pressure in its neighborhood but its volume depends first of all on the quantity and volume of the bubbles produced in the "factory of bubbles". The core volume depends also on the existence of obstacles downstream behind the wing. This dependence will be demonstrated in the next section containing the description of the experiment.

The dimensions of bubbles after the implosion determine whether the vortex cavitation gains the form of gaseous core. The acoustic emission caused by increasing and oscillating bubbles takes place before the cavitating core forms.

According to currently applied calculation models for the vortex cavitation (Rankine vortex [4]) the region which enables vortex cavitation inception covers the whole or almost the whole vortex core. This statement can not be confirmed by experimental results.

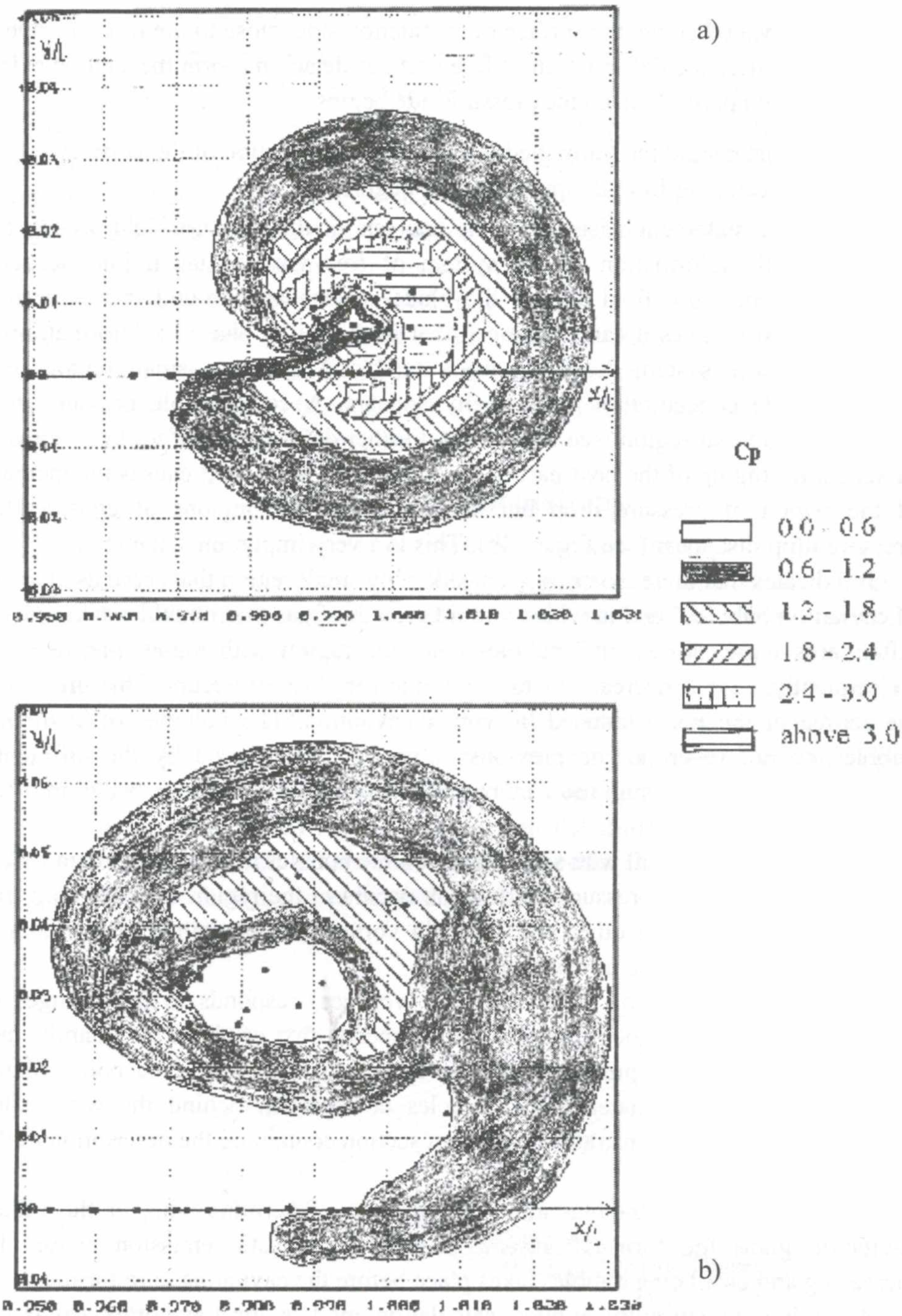

Figure 4. *Pressure field defined by isobars in the vicinity of a deforming free vortex surface for: a) $t_0 = 0.01$; b) $t_0 = 0.08$. x,y — ordinates in the systems linked to the wing; L_0 — half span of wing; t_0 — time related to $t=L_0/V_0$; V_0 — velocity of the undisturbed flow*

6. Experimental research

The most recent experimental research executed within the frames of the Scientific Research Committee research project provided very interesting results that might serve as the experimental verification of the temporary hypotheses associated with the calculation model for vortex cavitation on screw propeller blades. The results confirm the hypothesis concerning the limitations of the region where vortex cavitation inception takes place (factory of gas bubbles). It can be also concluded that the bubbles collapse as they move through a specific velocity and pressure field generated by deforming free vortices. That velocity field generated by detaching free vortices forms a characteristic trap for gas bubbles. In case of undisturbed flow (no obstacles behind the wing) a characteristic gaseous core of the tip vortex appears. If there is any obstacle behind the wing, the diameter of the vortex core increases upstream of the obstacle and only single bubbles can be noticed downstream the obstacle.

The similar effect was obtained incidentally during the experiments with a hydrofoil at the cavitation tunnel at Ship Design and Research Centre. For arbitrary flow conditions a large gaseous bubble appeared form downstream direction on the thin vortex core. Depending on pressure and velocity in the tunnel test section it approached towards the trailing edge of the hydrofoil or withdrew downstream from the hydrofoil (see Figure 5). In this case a guide vane located in the knee of the tunnel might serve as the obstacle (up to now it is only a hypothesis).

The first presentation of similar gaseous structure downstream the hydrofoil in the location of tip vortex can be found in [2]. The difference lies in that the air was artificially injected into the bubble in the reported case. The same way of obtaining of stable gaseous bubble is described in [12].

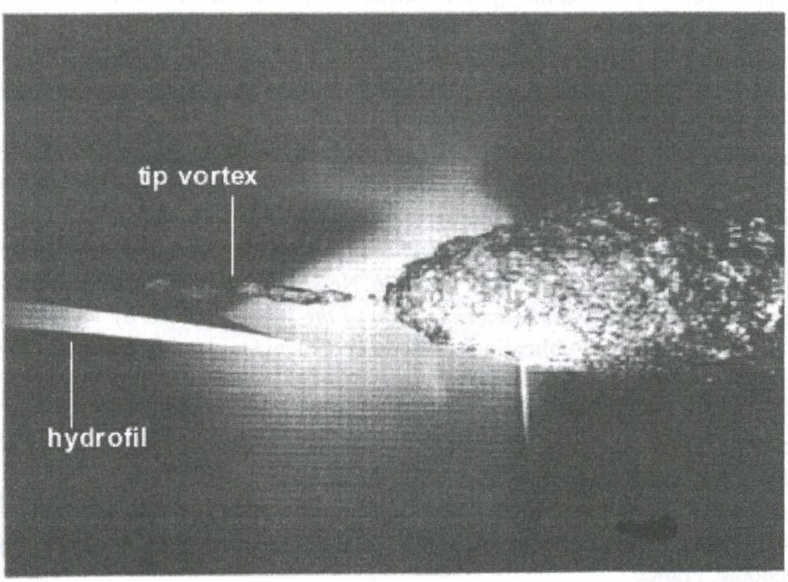

Figure 5. *Gaseous bubble behind a hydrofoil. The direction of the flow is from the left to the right*

The results of the experimental research as well as the results of calculations confirm the thesis of the existence of strictly limited region within which the vortex cavitation inception occurs and acoustic emission takes place. This region coincides with the initial deformation of free vortices (see Figure 3).

7. Concluding remarks

Typical form of vortex cavitation with gaseous core is only the picture of phenomenon that originates in different location. The Rankine vortex model is not sufficient for adequate description of all phenomena associated with vortex cavitation. It is suitable as far as the changes of volume of the developed vortex core are considered. It can not be applied for description of vortex cavitation induced noise, especially in the initial phase of vortex gaseous core development.

Thorough recognition of mechanism of vortex cavitation inception enables the effective avoiding of that source of noise generated by screw propellers. It enables also the improvement of computer programs for analysis of screw propeller operation in real scale.

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