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Theoretical and experimental investigation of the generation mechanism of tip vortex and vortex cavitation

SUMMARY

The paper presents the problem of tip vortex cavitation inception in the flow around a screw propeller. The most recent experimental and theoretical results concerning mechanisms of tip vortex generation and vortex cavitation inception are reported.

INTRODUCTION

Low level of the screw-propeller-induced noise is of crucial importance for proper operation of naval and geophysical ships. Therefore experimental and theoretical research aiding low-noise propeller design is carried out by world leading research institutions. In principle, a screw propeller free from cavitation serves as an example of low-noise propeller. Usually, vortex cavitation is the first form of cavitation that appears in the vicinity of screw propeller when its loading increases. Hence the screw which operates without tip vortex cavitation could be deemed a low-noise propeller [5,6,8].

Tip vortex cavitation does not generate any disadvantageous effects in the flow except the noise and increase of pressure pulsation on a ship hull surface. It does not decrease either the efficiency of a propeller or cause its erosion. This is why vortex cavitation mainly focuses the interest of research institutions working for the navy. Results of such research are often confidential.

Investigation of screw-propeller-induced noise were originated at the Institute of Fluid Flow Machinery in the 1980s. A methodology of design of low-noise screw propellers and computer design program were developed.

The work on the problem was continued and consequently two research projects were run supported by the State Committee for Scientific Research (KBN). The first of them consisted in development of a computer program for detection of vortex cavitation on a propeller blade [4]. The second one was focused on experimental verification of the theoretical model of the phenomena connected with the formation of vortex cavitation on a propeller blade. This paper presents theoretical and experimental results of the above mentioned projects.

A DOUBLE-LAYER LIFTING SURFACE MODEL

A theoretical model of the flow around screw propeller blade tip and of formation of tip vortex was developed in the 1980s. An original, new approach, based on double-layer lifting surface concept was applied [3].

The most important features of the theoretical model are as follows :

- only lifting vorticity is taken into consideration (i.e. that component of total vorticity which arises from asymmetry of the flow around a profile and is strictly related with ascend of lift force on a foil)
- vorticity is distributed on both (i.e. suction and pressure) sides of a foil
- free vorticity detaches from pressure and suction sides independently.

A comparison of two different lifting surface models, i.e. the classical one (of single-layer) and that of double-layer, is presented in Fig 1a and 1b, respectively.

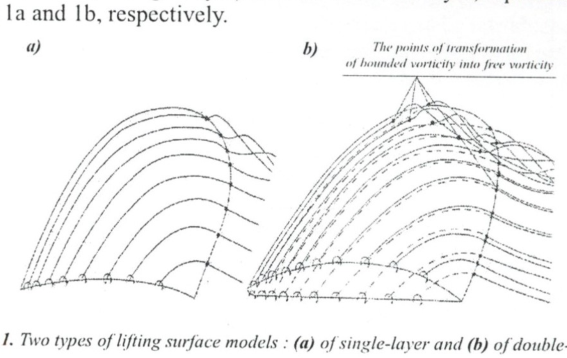

Fig.1. Two types of lifting surface models : (a) of single-layer and (b) of double-layer

Application of the new calculation model for determination of the flow around a screw propeller blade provided qualitatively new results. Conditions sufficient for vortex cavitation inception can now be found in the initial part of the deforming system of free vortices. A critical pressure drop leading to rapid growth of vapour-gas microbubbles occurs in the region located in the vicinity of blade tip. The set of free vortices detaching from the suction side and the set of vortices shedding from the trailing edge (see Fig.3) both serve as two cavitation bubble „factories".

This statement arises from the analysis of pressure field around the blade tip, which accounts for deformation of bounded vorticity system. On the basis of examination of the pressure field in the vicinity of blade surface and around the deforming free vortices it can be concluded that a relatively small region of high vorticity concentration arises there. A considerable pressure decrease occurs within this region (Fig.2a). Further deformation consists in spiral winding of free vortices around a vortex core. It makes the extent of low-pressure region increase. Nevertheless, the sub-regions of significant pressure drop disappear (Fig.2b).

The calculation models of vortex cavitation [2] used so far predict that the region of the pressure drop sufficient for cavitation forming coincides with the entire developed tip-vortex core or at least with a considerable part of it. Results of a thorough theoretical and experimental study indicate that the region of cavitation inception is much shorter and does not exceed the blade outline (Region 1 in Fig.3). Additionally, outside the blade outline (just behind the trailing edge) another region of vortex cavitation inception can be found. This second region is formed by the free vortices detaching from the pressure side and crossing the trailing edge. Behind the trailing edge the next small region can appear of the considerably low pressure sufficient for explosive growth of microbubbles.

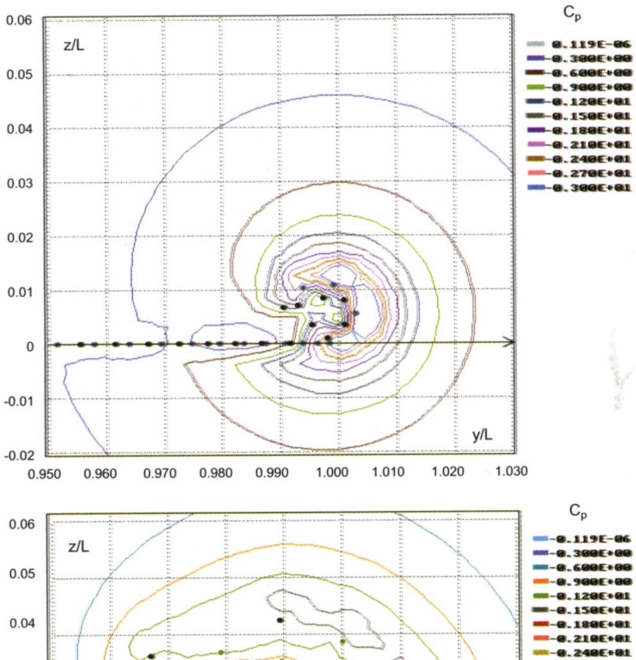

Fig.2. Isobars of the pressure field in the vicinity of deforming free-vortex system ***a)*** *at $t_0 = 0.01$,* ***b)*** *at $t_0 = 0.08$*

Notation : *y, z - system of co-ordinates connected with a hydrofoil, t_0 - relative time of free vortices deformation (with respect to L/V_0), L= wing span, V_0 - undisturbed flow velocity, Cp - pressure (negative pressure) coefficient*

Those relatively small regions located close to the tip, i.e. above the blade surface and just behind the blade, serve as the „factories" of cavitation bubbles. A rapid growth of microbubbles occurs inside the regions. Then the „already grown" bubbles enter the region of higher pressure where their volumes rapidly decrease. Such implosions are the main source of the noise generated by vortex cavitation. Although the implosion occurs the volumes of bubbles do not reach previous values. It is due to the different duration times of two opposite processes i.e. bubbling and gas absorption in water. The diminished, but still significantly voluminous bubbles move through a specific velocity and pressure field trapped inside the deforming system of free vortices. They join together and form the characteristic cavitating vortex core.

The cavitating core of the vortex behaves according to pressure changes in its vicinity, but its shape and volume depends mostly on quantity and volume of gaseous bubbles arising in the „cavitation bubble factories". It will be shown that the behaviour of vortex core is related with the presence of obstacles located downstream the foil.

Two specific regions can be distinguished for typical foil shapes and load distributions. The regions are presented in Fig.3.

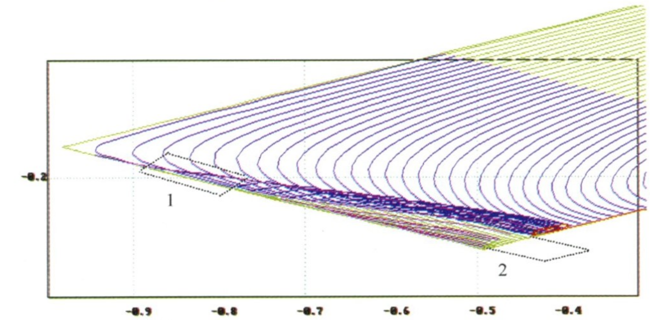

Fig.3. Regions of possible cavitation inception

Region 1 – Located above the suction side surface, close to the leading edge, where the deformation begins of free vortices detaching form the suction side and partially from the pressure side.

Region 2 – Located just behind the trailing edge, where deformation of the vortices detaching from the pressure side begins.

The process of growth and disappearance of gaseous bubbles is the source of the noise induced by vortex cavitation. An analytical description of the behaviour of spherical gaseous bubbles in a certain pressure field is given by Rayleigh-Plesset equation [7].

The size of the bubbles after their implosion determines whether the voluminous vortex cavitation develops or not. Emission of the noise generated by expanding and oscillating gaseous microbubbles takes place earlier than formation of the vortex core. Dependent on flow parameters, bubbles undergo cyclic oscillations with specific frequencies. It has been proved experimentally that the acoustic emission frequency due to vortex cavitation inception reaches several thousand Hz. The increase of load connected with simultaneous growth of gaseous bubbles causes decrease of the acoustic emission frequency. The growing bubbles join together and form continuous, gaseous vortex core as the intensity and frequency of the noise generated by vortex cavitation changes. In this case the variation of vortex core volume becomes an additional source of noise. The oscillations of vortex core volume are caused by circumferential nonuniformity of propeller blade loading due to propeller operation behind a hull. Therefore frequency of oscillations of vortex core volume are strictly related with number of blades and propeller rotation.

CALCULATION ALGORITHM

The calculation model is based on the laws governing potential flow induced by a system of vortices distributed in a finite domain [1,3]. The calculation procedure is a typical iterative process. A set of vortices distributed both on the pressure and suction side (double-layer lifting surface) is a starting point for calculations. In the case of design, (foil geometry is unknown) a distribution of loading as well as its magnitude can be assumed, and in the opposite case (of analysis) foil geometry and appropriate boundary conditions are supposed to be known. In the latter case loading is determined with the use of one of already developed methods.

In both cases the initial sets of free vortices are undistorted and their detachment points are located on the trailing edge. An example of the initial distribution of vortices on a rectangular foil surface is presented in Fig.4.

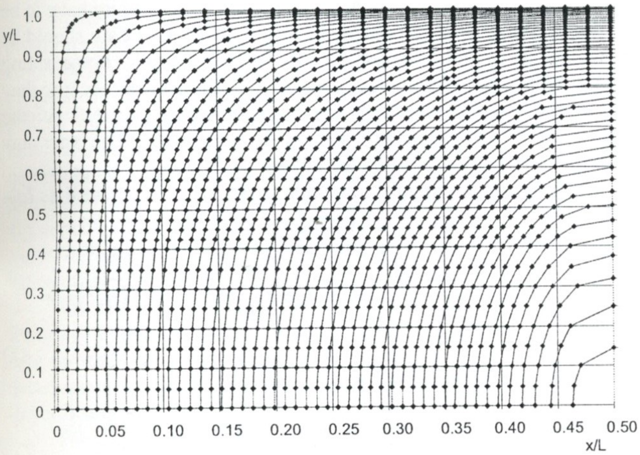

Fig.4. Initial distribution of vortex filaments on the suction side of a rectangular foil

The first step of calculations consists in adding a set of free vortices. This is done in the classical manner, i.e. by applying half-infinite vortex filaments shed from the trailing edge as a continuation of bounded vorticity. In the case of a foil they are half-infinite straight lines, and in the case of a screw propeller they gain the shape of half-infinite helical lines.

In the next step, normal component of velocity is determined in the points coinciding with vortex filaments location. The Biot-Savart rule for a straight section of vortex filament is applied. An example of the calculated velocity is presented in Fig.5.

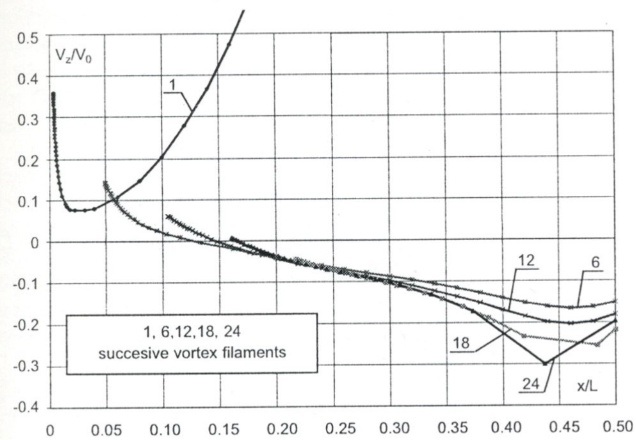

Fig.5. Normal component of induced velocity along certain vortex filaments

The initial results are stored as *the base velocities*, V_b. It can be concluded from Fig.5 that when all filaments of bounded vorticity lie on the foil surface and the shape of free vortices remains constant, then only the most outer vortex filament on the suction side gains a considerably large value of the velocity normal to the foil surface. The most outer filament detaches from the foil surface at the point where it reaches a certain velocity value (the separation velocity). The successive step of calculation indicates that the same situation occurs with the next vortex filament. A new location of vortex filaments is determined by assuming appropriate time steps. The time step of calculations is adjusted by using the magnitude of translation of the vortex filament from the separation point (where normal velocity gains its extreme value). Nevertheless the translation of vortex filaments requires fulfiling certain conditions.

The velocity V_z resulting from the determined normal component of the induced velocity and base velocity has to be :

- directed outwards the foil surface
- greater than a certain velocity value, the *separation velocity* V_s.

The separation velocity can be interpreted in the following way. If $V_z \geq V_s$ then bounded vortex filament becomes a free vortex and moves along a streamline. In opposite case, i.e. when $V_z < V_s$, the velocity V_z is compensated by an additional bounded vorticity. The distribution of vorticity magnitude changes, and the location of vortex filaments on a foil surface changes too. A secondary vorticity appears at the location of the already detached vortex filaments.

Therefore further steps of the calculation consist in determination of the following quantities :

- ✧ new location of all vortex filaments (bounded and free)
- ✧ induced velocities
- ✧ secondary vorticity in the location occupied by bounded vortices before their detachment.

SECONDARY AND COMPENSATING VORTICITY

A vortex formation (hereafter called „pocket") arises within a region located close to the tip of a foil. This pocket is a region limited by the following vortex surfaces (see Fig.6) :

- set of vortices detaching from the suction side
- set of vortices detaching from the pressure side and crossing the tip edge
- new set of vortices arising on the suction side, i.e. secondary vorticity which replaces the already detached bounded vorticity.

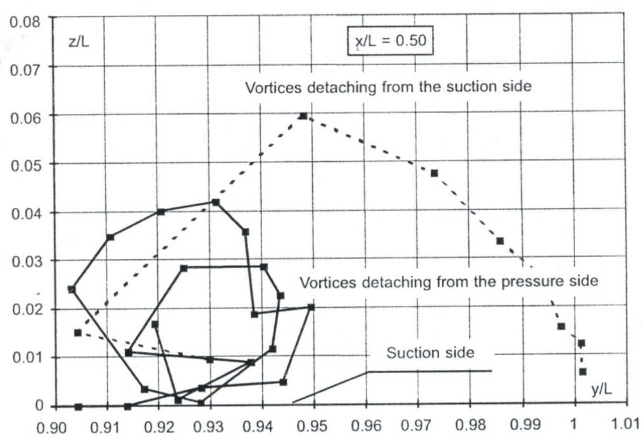

Fig.6. A cross-section through the deforming free vortices shedding from the suction and pressure side of the rectangular hydrofoil. The vortices together with the foil surface form a „pocket".

In order to properly calculate the secondary and compensating vorticity on both sides of the foil transverse vortex elements have to be introduced (Fig.7). The transverse vortices can be introduced only for the vortex elements whose y- co-ordinate (along foil span) is greater than a certain value. This value is determined by the variation of normal component of induced velocity at the location of control points.

Due to the conservation law of vorticity the intensities of transverse vortices are strictly related with longitudinal vortices. Therefore the number of unknown parameters does not increase.

The procedure of introduction of transverse vortex elements is executed for both sides of a foil.

Variation of vorticity due to separation of vortices from the foil surface and relative motion of free vortex filaments is taken into account while formulating the set of equations for determination of vorticity distribution between two successive steps of calculation.

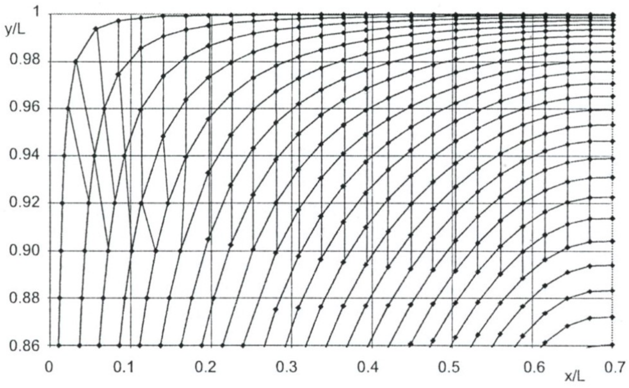

Fig.7. A net of vortex elements completed with transverse elements

A SET OF EQUATIONS FOR DETERMINATION OF SECONDARY AND COMPENSATING VORTICITY

A set of equations for determination of compensating vorticity is obtained by subtracting mutually corresponding components (for identical control points) of two successive sets of equations formulated for two successive steps of calculation. The sets of equations are constructed on the basis of the Neumann's boundary condition which consists in equalizing to zero the normal component of velocity on the foil surface.

Additionally the set of equations fulfils the following assumptions :

- ✶ control points are located at the beginning of each vortex element
- ✶ the angle of attack of the foil is small enough for the normal component of velocity at each of the control points to be estimated by z-component of velocity.

The z- component of induced velocity at the control point of the co-ordinates : x(n,i) , y(n,i) , z(n,i) can be derived from Biot-Savart equation as a sum of velocities induced by vortex elements as follows :

$$V_Z(n,i)_k = \sum_{i=1}^{N1}\sum_{n=1}^{NT2(i)} A(n,i)\cdot S(n,i)_k + \sum_{i=1}^{Nd}\sum_{n=NT2(i)}^{NT1(i)} G(n,i)_k\cdot S(n,i)_k \tag{1}$$

where:

$A(n,i)=\frac{\Gamma_{max}}{2N1}$ - intensity of the vortex element located outside a pocket

Γ_{max} - the maximum value of circulation on a foil

G(n,i) - intensity of the vortex element located inside a pocket (secondary vorticity)

N_d - the number of vortex filaments detaching from the foil surface in front of the leading edge, equal to the number of vortex filaments in the pocket

N1 - the number of vortex filaments on one side of the foil

NT1(i) - the number of vortex elements contained by i-th vortex filament

NT2(i) - the number of vortex elements contained by i-th vortex filament in front of the pocket

S(n,i) - the part of Biot-Savart equation resulting from the relative location of vortex filament and control point

Vz - the velocity resulting from the normal component of the induced velocity and base velocity

k - calculation step.

For the primary set of vortices it is assumed that A(n,i) = const. for each of all vortex elements. During the successive calculation step the intensity of vortex elements can change. It means that unambiguous determination of direction and value of vorticity field on the foil surface requires introduction of transverse vortex elements (Fig.7). In two next steps of calculations such changes of z-component velocity, $V_Z(n,i)$, at control point are expected. The changes are caused by possible detachment of a vortex filament from the foil or by the translation of free vorticity filaments. The changes of vorticity have to be consistent with the Neumann's condition. Therefore they should be compensated by the additional vorticity G(n,i) (both compensating and secondary vorticity are denoted in the same manner because they are derived from the same equation) or should be associated with the detachment of a vortex filament from the foil surface. The latter possibility is a novelty in vortex modelling.

The z-component of induced velocity can be obtained as follows :

$$V_Z(n,i)_{k+1} = \sum_{i=1}^{N1}\sum_{n=1}^{NT2(i)} \left[A(n,i)+G(n,i)_{k+1}\right]\cdot S(n,i)_{k+1} + \sum_{i=1}^{N_d}\sum_{n=NT2(i)}^{NT1(i)} G(n,i)_{k+1}\cdot S(n,i)_{k+1} \tag{2}$$

where :

$G(n,i)_{k+1}$ - secondary or compensating vorticity in (k+1)-th step of calculations.

The unknown vorticities $G(n,i)_{k+1}$ appear on a certain vortex filament (compensating vorticity) or at the previous location of already detached, bounded vorticities (secondary vorticity). This additional vorticity compensates the changes of the normal component of induced velocity. The set of equations enabling determination of the unknown vorticities $G(n,i)_{k+1}$ is obtained by subtracting the equations (1) from (2), namely :

$$\Delta V_Z(n,i)_{k+1} = V_Z(n,i)_{k+1} - V_Z(n,i)_k =$$

$$= \sum_{i=1}^{N1}\sum_{n=1}^{NT2(i)} G(n,i)_{k+1}\cdot S(n,i)_{k+1} + \sum_{i=1}^{Nd}\sum_{n=NT2(i)}^{NT1(i)} (G(n,i)_{k+1}\cdot S(n,i)_{k+1} + \tag{3}$$

$$- G(n,i)_k\cdot S(n,i)_k) +$$

$$+ \sum_{i=1}^{N1}\sum_{n=1}^{NT2(i)} A(n,i)_{k+1}\cdot\left[S(n,i)_{k+1} - S(n,i)_k\right]$$

Calculation of the compensating vorticity is supplemented by correction of location of vortices outside the pocket. It makes it possible to determine the initial intensity A(n,i) of vortex elements in the successive step of calculation. The correction of location of the vortices distributed on the pressure side of the foil is necessary in the case of translation of vortex filaments beyond the tip edge.

The solved problem of proper modelling of the flow around a foil tip, inclusive of arising of a vortex „pocket" as well as applying the double layer lifting surface model, is a novelty. The problem was solved by the „trial-and-error" method. By keeping to the laws governing the vortex flow different simplifications can be made.

The simplifications may concern the shape of vortex filaments, number of vortex filaments, location of control points and shape of the vortex mesh (in the case of compensating and secondary vorticity).

Several tentative hypotheses have been formulated. The most important of them concerns the limit value of normal component of velocity, at which the lines of vortex field (in the calculation model of vortex filaments) start to separate from the foil surface in the double-layer lifting surface model. A proper verification of this hypothesis requires a thorough experimental research.

EXPERIMENTAL RESEARCH

In the 1980s an extensive experimental and theoretical research program was carried out at the Institute of Fluid Flow Machinery in co-operation with the Maritime Technique Centre. The aim of the program was to develop a methodology of design of low-noise propellers. Many model tests of screw propellers were executed in a cavitation tunnel within the frames of this program. The research concerned the noise associated with different forms of cavitation. Its results confirmed the importance of the problem of noise generation by tip vortex cavitation. Semi-empirical coefficients for prediction of vortex cavitation development were derived and guidelines for elaboration of calculation models and computer programs were developed.

The aim of recent experimental research carried out within the frames of a research project supported by KBN, was to provide the data for elaboration of criteria concerning location of the vorticity detachment points on the foil surface, with the use of the double-layer lifting surface approach.

The experimental research consisted in LDV (Laser Doppler Velocimetry) measurements of velocity field in the flow around hydrofoils. An analysis of experimental results and their comparison with calculation results led to the following conclusion : the best correlation was obtained for the relative velocity V_z/V_0 contained within the range of 0.4÷0.6.

The scatter of the results was caused by two factors: measurement uncertainty and imperfectness of the model. The results obtained from the experiments confirmed the correctness of the tentative hypotheses formulated for the calculation model of vortex cavitation on screw propeller blades. Occurrence of the limited regions (cavitation bubble „factories") in the blade tip vicinity where cavitation inception takes place, was proved. After a growth period, volumes of the bubbles decrease as they move with the flowing water. The cavitation bubbles move through a specific velocity and pressure field determined by the deforming free vortices. This velocity field becomes a specific trap for cavitation bubbles. When the downstream zone of the flow remains undisturbed then a characteristic gaseous tip vortex core arises.

A very interesting effect was observed during examination of tip vortex in the cavitation tunnel of the Ship Design and Research Centre (CTO). At certain parameters of the flow a stable gaseous pocket was arising behind the trailing edge of the hydrofoil, in the location of the tip vortex. Instead of a thin gaseous core a voluminous vortex core appeared. A position of this bubble with respect to the hydrofoil could be controled by changing pressure and velocity inside the test section (Photo).

Such a gaseous form behind a hydrofoil inside a tip vortex was presented in [2], but in that case the air was artificially supplied to the bubble. The same way of obtaining stable bubbles is described in [9].

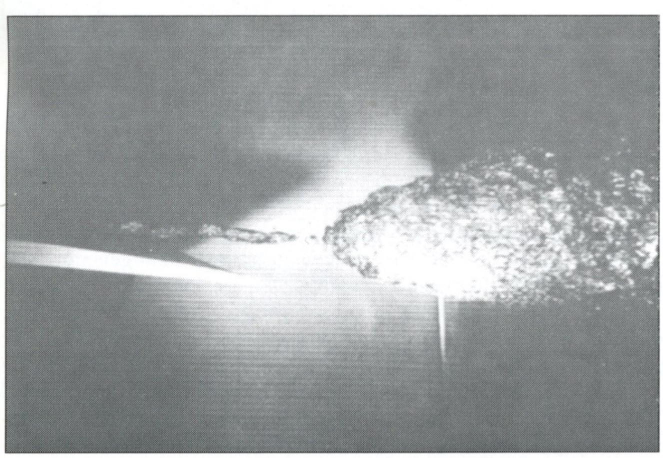

Photo. A voluminous tip vortex cavitation

The experimental research and calculation results confirm that the region of initial, intensive deformation of free vortices serves as the source of the noise induced by tip vortex cavitation (such regions are marked in Fig.3).

CONCLUDING REMARKS

The aim of the research reported in the paper is to elaborate a new, more adequate theoretical model of tip vortex cavitation. The proper recognition of the noise generation mechanisms associated with vortex cavitation makes it possible to elaborate the effective methods of avoiding it. The presented model can easily be developed into a numerical procedure and included in the programs for analyzing screw propeller operation. Obviously it would improve the calculation model of screw propellers.

BIBLIOGRAPHY

1. Batchelor G.K.: „An Introduction to Fluid Dynamics". Cambridge, 1970
2. McCormick B. W., Jr.:"On Cavitation Produced by a Vortex Trailing from a Lifting Surface". Journal of Basic Engineering, September 1962
3. Koronowicz T.: „Theoretical Model for the Stream Behind a Screw Propeller Based on the Concentrated Vorticity with Cavitation Core and Hydrodynamical Characteristics of the Helical Vortex System within the Limited Region" (in Polish). Bulletin of IFFM no. 58/956/79
4. Koronowicz T., Szantyr J., Tuszkowska T., Waberska G.: „KAWIR - a Computer Program for Determination of Noise Generated by Vortex Cavitation on Screw Propellers" (in Polish). Report of IFFM no. 179/94
5. Koronowicz T.: „Vortex Cavitation as the Source of High Level Acoustic Emission of Screw Propellers" (in Polish),. Proceedings of the 11th Symposium on Hydroacoustics. Gdynia-Jurata, 1994
6. Koronowicz T., Tuszkowska T.: „Selected Problems of Design of Low Noise Screw Propellers" (in Polish). Proceedings of the 5th Symposium on Naval Technique. Gdynia, 1995
7. Koronowicz T., Szantyr J.:"A New Theoretical Model of Formation of Vortex Cavitation". Proceedings of PROPCAV'95. Newcastle upon Tyne. May 1995
8. Koronowicz T.: „Analytical Determination of the Noise Induced by Vortex Cavitation on Screw Propellers" (in Polish). Publications of Technical University of Łódź. Thermal Flow Machines no. 110/1996
9. Meijer M.C.: „Swimming Vortex Cavities". Euromech Colloquium 146. Grenoble, September 1981

Conference

ZTM Gdansk Gdynia Szczecin

Marine Technology Unit

On 3 April 2000, Marine Technology Unit (acting within the Section of Transport Technical Means, Transport Committee, Polish Academy of Sciences) held its first-of-the-year meeting hosted by the Faculty of Ocean Engineering and Ship Technology, Technical University of Gdańsk. During the scientific part of the meeting the following papers were presented and discussed :

- *Occurrence identification of unstable and non-stationary temperature and pressure of the gases behind the turbine combustion chamber* (by M.Dzida, D.Sc)
- *Formulation of the availability of sea transport means* (by Prof., J.Girtler)

In the next part of the meeting the organizational matters were considered connected with commencement of another 3-year term of activity of the Unit under chairmanship of Prof. J.Girtler, the Head of Ship Power Plant Dept., Faculty of Ocean Engineering and Ship Technology, Technical University of Gdańsk, and with Z. Matuszak, D.Sc., of Maritime Technology Faculty, Technical University of Szczecin, as its secretary.