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The Influence of Viscous Effect on Design of the Optimal Supercavitating Hydrofoil with Spoiler

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ABSTRACT

The goals of this paper are:

- to study the influence of fluid viscosity upon the hydrodynamic characteristics of the supercavitating hydrofoil with spoiler mounted on its trailing edge, and
- to produce a method of designing of an optimal supercavitating hydrofoil with spoiler operating in the viscous flow.

The analytical and numerical investigations, as well as experiments, show that the stagnation zone appears in the spoiler vicinity due to separation of the boundary layer in turbulent flow regime. This leads to the fact that the spoiler partially immerses into the boundary layer and, as a result, reduces its effective length. This is why the design process of an optimal shape of the supercavitating hydrofoil with spoiler has to take into account fluid viscosity.

Keywords

supercavitating hydrofoil, spoiler, viscous effects

1 INTRODUCTION

Back in the 1980's in the Soviet Union, the supercavitating screw propellers were mounted on hydrofoil "Antarias", which had a displacement of 200 t and speed 60 knots. Spoilers installed on the blades' trailing edges of the screw propellers prevented breakthrough of the atmospheric air along inclined shafts to the blades on speed of about 50 knots. The further development of propulsors for fast ships continues to attract additional attention to the design of screw propellers with spoilers, which ensure a higher effectiveness and strength of blades' leading edges (Achkinadze & Fridman 2000).

A combination of asymptotic and numerical methods is used in this paper to obtain an optimal shape of the supercavitating hydrofoil under a set of geometrical and hydrodynamic conditions, such as conditions on cavity and hydrofoil thickness, on pressure distribution, etc. Some numerical results are demonstrated to be in good agreement with data of experiments. Viscous effects are taken into account using a CFD approach.

The authors believe that current progress in the design of supercavitating screw propellers can make such types of propulsors applicable for fast ships (with speeds above 60 knots) and will breathe new life into the brilliant ideas of the academician V.L. Pozdjunin (Pozdjunin 1944).

2 FORMULATION IN THE FRAMEWORK OF THE LINEAR THEORY

Let's consider free surface flow past a flat plate of chord l inclining an angle of attack α to the far stream flow, with the relative spoiler length ε, forming the incidence angle β between spoiler and flat plate. It is necessary to take such parameters into account in order to achieve the outer asymptotic solution of the supercavitating flat plate. The origin of the coordinates is located at the leading edge, and x-coordinate is directed parallel to the far stream velocity vector. If the opened cavity closure scheme is used, the complex conjugate velocity will be as follows:

$$\chi(\varsigma) = 1 + i\alpha + iC\sqrt{\frac{\varsigma + a}{\varsigma}} + \frac{iB}{\sqrt{\varsigma(\varsigma + a)}}\ ; \qquad (1)$$

$$\varsigma = \sqrt{\frac{z}{L - z}}\ ; \qquad (2)$$

The length of cavity $L = \cos^{-2}(\tau/2)$. The parameter $a = ctg(\tau/2)$, where τ is auxiliary variable.

$$\begin{cases} C = sin^{-\frac{1}{2}}\frac{\tau}{2}\left(\frac{\sigma}{2}\, sin\frac{\pi - \tau}{4} - \alpha\, cos\frac{\pi - \tau}{4}\right); \\ B = sin^{-\frac{3}{2}}\frac{\tau}{2}\left(-\frac{\sigma}{2}\, cos\frac{\pi - \tau}{4} + \alpha\, sin\frac{\pi - \tau}{4}\right); \\ \sigma = 2\,\alpha\, tg\frac{\pi - \tau}{4} + \frac{4\beta}{\pi}\sqrt{\frac{\varepsilon}{R}}\, sin\frac{\pi - \tau}{4} sin^{-\frac{1}{2}}\frac{\tau}{2}\ , \end{cases} \qquad (3)$$

where σ is cavitation number and:

$$R = \int_0^1 \xi\,\left(\frac{1 + \xi}{1 - \xi}\right)^{\beta/\pi} d\xi.$$

where ξ is integration variable.

Hydrodynamic lift and drag coefficients are:

$$C_L = \frac{\pi\alpha}{1+sin(\tau/2)} + 2\beta\sqrt{\frac{\varepsilon}{R}}\, sin^{-\frac{1}{2}}\frac{\tau}{2}\, cos\frac{\pi-\tau}{4} \quad (4)$$

$$C_D = \frac{\pi\,\alpha^2}{1+sin(\tau/2)} + 2\alpha\beta\sqrt{\frac{\varepsilon}{R}}\, sin^{-\frac{1}{2}}\frac{\tau}{2}\, cos\frac{\pi-\tau}{4} + \frac{2\beta^2}{\pi}\frac{\varepsilon}{R} + C_f, \quad (5)$$

where C_f − skin frictional coefficient.

The form of cavity is easily defined by integrating the complex conjugate velocity (Gurevich 1979).

In Figure 1, the results of the calculation of flow past SC foil is depicted for the set of parameters, $\sigma = 0.35$, $\alpha = 3°$, $\beta = 90°$, $\varepsilon = 0.01$. Hydrodynamic lift in this case is 0.614, corresponding length of cavity, L = 1.02. The frictional coefficient, $C_f = 0.0025$, is derived from Reynold's number (Zaw Win et al 2010).

$$Re = u_\infty\, l/v \quad (6)$$

$$C_f/2 = 0.037\, Re^{-1/5} \quad (7)$$

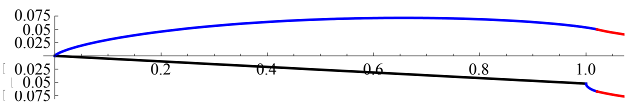

Fig.1: Flow past SC foil with the parameter set; $\sigma = 0.35$, $\alpha = 3°$, $\beta = 90°$, $\varepsilon = 0.01$

3 VISCOUS FLOW MODEL THROUGH COMPUTATIONAL FLUID DYNAMIC

After having predicted the cavity's shape above the hydrofoil through linear theory, one can configure the body consisting of the lower wetted surface of the foil including spoiler, the upper cavity surface and semi-infinite wake in GAMBIT. Then the boundary conditions are defined in FLUENT. The upper cavity surface is as a slip wall, the lower wetted part of the foil as non-slip wall, and semi-infinite wake as a symmetric boundary or slip wall, see figure 2. The mesh elements in this paper are created about 258000 including boundary layer with minimum nearest cell thickness y_p of 0.005 mm. One can determine the minimum cell thickness by using Equation (8) (Zaw Win et al 2010):

$$y_p = y^+ v/(u_\infty\sqrt{C_f/2}), \quad (8)$$

where $y^+ > 30$ or $y^+ < 5$.

One can carry out the calculation and modelling of the viscous flow past the SC foil by means of RANS solver of FLUENT when the meshing is complete in GAMBIT. The Spalart-Allmaras (S-A) model is chosen because it is suitable for the 2-D flow past hydrofoil in turbulent flow regime. In this paper, the flow model is set up with the following parameters (Hong Son 2008):

Reynolds No.:	- 2.1×10^7
Chord length:	- 1 m
Inflow velocity:	- 23.86 m/sec
Density of water:	- 999 kg/m^3
Kinematic viscosity of water:	-1.14×10^{-6}m^2/sec
Density of water vapor:	- 0.015 kg/m^3
Kinematic viscosity of water vapor:	- 6×10^{-5} m^2/sec
Saturated vapor pressure:	- 1700 Pascal

The iteration is complete when the convergence of continuity equation reaches the value of 10^{-5}, which is one of the convergent criteria of the residuals. The numbers of iteration were undertaken about 3500 in this case. Then the flow type has to be changed as multi-phase flow and the cavitation mode is turned on to consider the cavitating flow model.

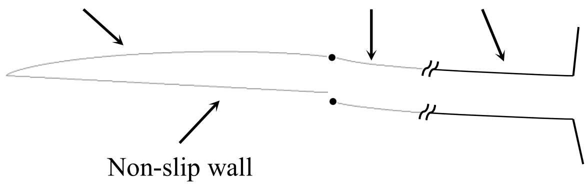

Fig. 2: The configuration of body in preprocessing phase of CFD

In post-processing, the lift coefficient in CFD is compared with that of linear solution. If the former is less than the latter, the spoiler length has to be lengthened to some extent, the other parameters being
kept constant. Then the iterations are repeated in the procedure mentioned above until lift coefficient is identical between the two methods. As for given problem, Fluent found that the relative spoiler length is 0.0187 to get the same lift while the relative spoiler length was set as 0.01 in linear problem.

The pressure coefficients' distribution in flow domain is depicted in Figure 3. The white colour region is cavity. The Figure 4 shows the wall y^+ distribution on hydrofoil and cavity. The y^+ is defined as $y^+ = \frac{u_* y}{v}$ where u_* is frictional velocity near wall. In this paper, u_* is assumed zero on the cavity because of slip boundary.

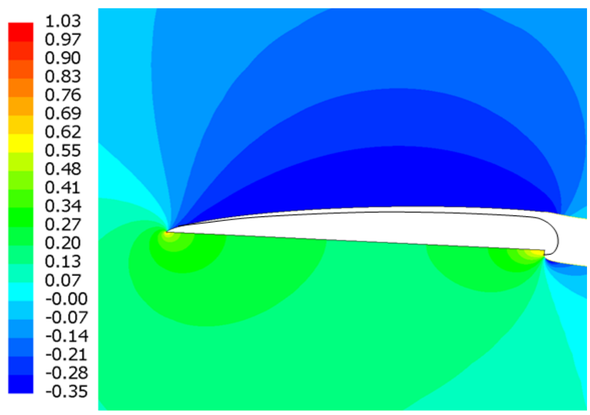

Fig. 3: The pressure coefficients' distribution

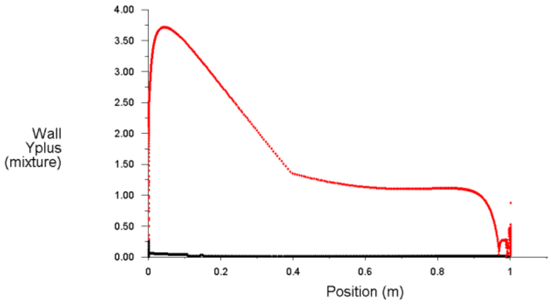

Fig. 4: The wall y^+ distribution on hydrofoil (red) and cavity (black)

4 COMPARISON OF RESULTS BETWEEN LINEARIZED METHOD AND CFD

It is noticed that the pressure coefficient curves between linearized method and CFD are nearly similar except leading and trailing edge, see Figure 5(a) and (b). Figure 6 shows the spoiler length ratio of CFD to linear theory with respect to angle of attack, the lift coefficient and geometry resulting from linear solution being kept constant except spoiler. It reveals that the spoiler length computed by Fluent is longer than that in linear.

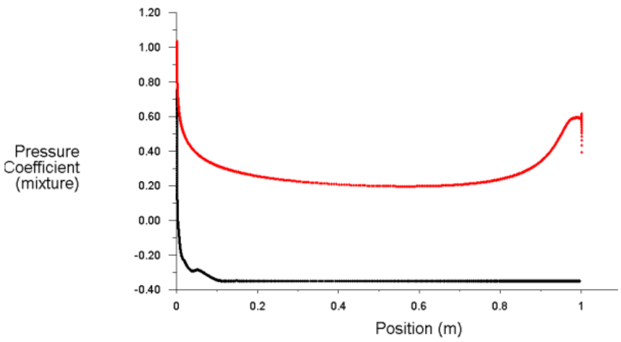

Fig. 5(a): The pressure coefficients on hydrofoil (red) and cavity (black) resulting from CFD

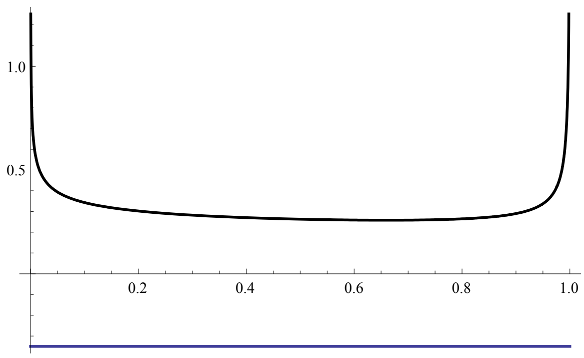

Fig. 5(b): The pressure coefficients on hydrofoil (black) and cavity (blue) resulting from linear theory

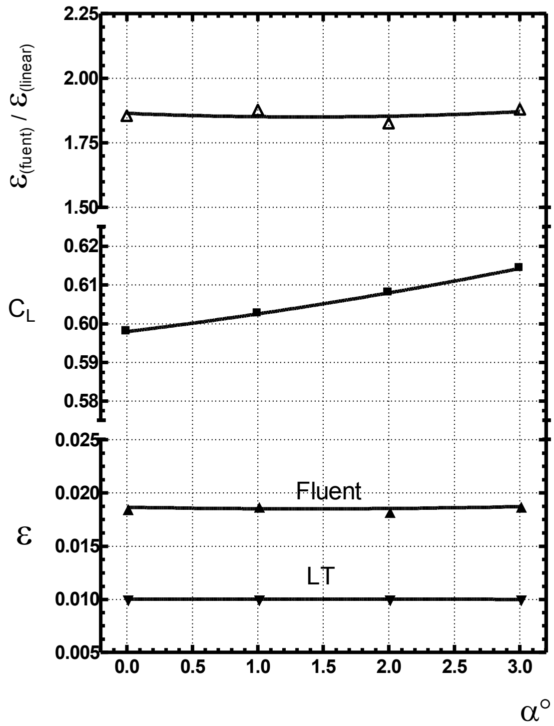

Fig. 6(a): The relative spoiler ratio of CFD to linear theory versus angle of attack on the basis of unique lift coefficient of linear theory for spoiler, ε = 0.01

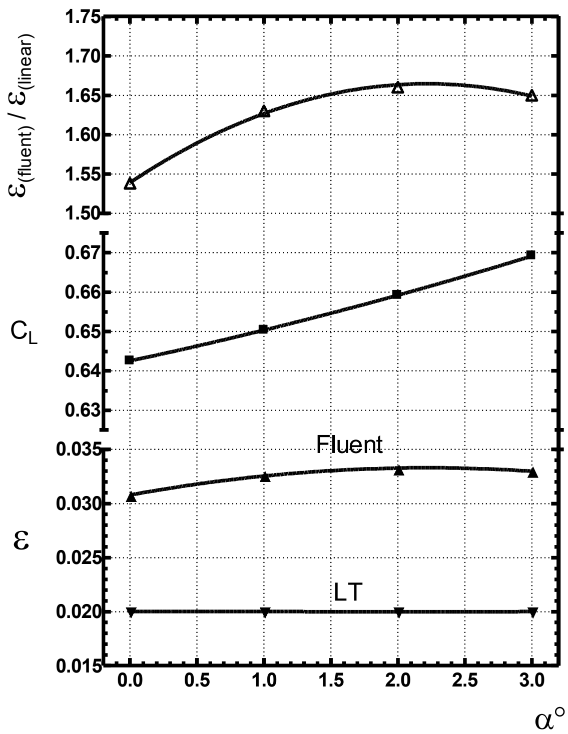

Fig. 6(b): The relative spoiler ratio of CFD to linear theory versus angle of attack on the basis of unique lift coefficient of linear theory for spoiler, ε = 0.02

5 CONCLUSION

This paper reveals that the hydrodynamic characteristics of the flow past the supercavitating hydrofoil resulting from the linear theory agree with CFD if one enables to adjust the spoiler length in the framework of CFD. That is why the CAE method does not take into account the stagnation zone, which occurs due to boundary layer separation of the viscous flow near the corner of the spoiler and the lower flat plate of the hydrofoil. One can design the SC foil by using the algorithm mentioned in the introduction of this paper. The geometry of hydrofoil and cavity can easily be determined by the non-viscous linearized method. The optimum hydrofoil can also be found first within a few moments by such method. Then some iterations have to be done in CFD program until the desired lift coefficient will be met.

Figure 7a demonstrates an S-shaped supercavitating hydrofoil with spoiler designed on the basis of the proposed approach with maximum lift-to-drag ratio and sufficient thickness of the leading edge (Win 2010). Pressure distribution coefficient on the hydrofoil is shown in Figure 7b.

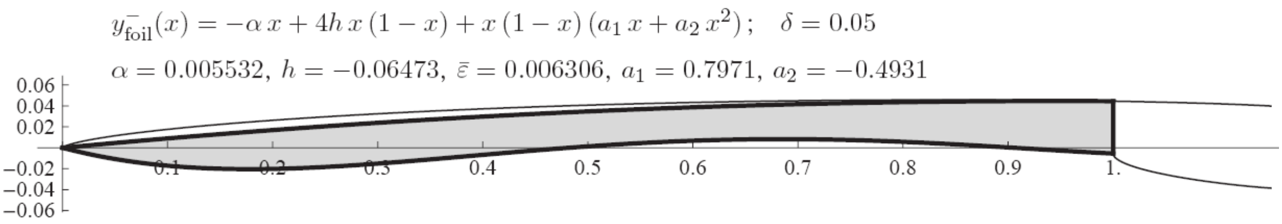

Fig. 7(a): An optimal S-shaped supercavitating hydrofoil with spoiler

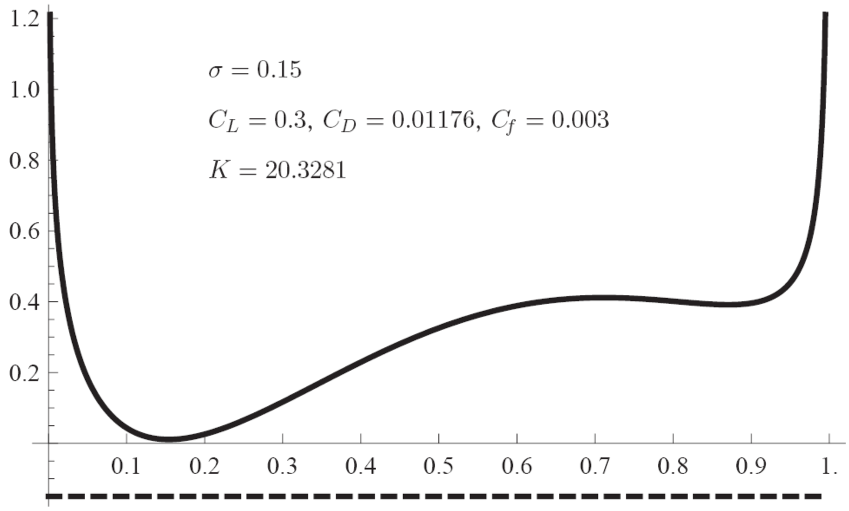

Fig. 7(b): Pressure distribution coefficient

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