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APPLICATION OF OPTIMIZATION METHODS IN 2D HYDROFOIL DESIGN

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Abstract

Modern computer technologies allow us to conduct rather complex mathematical calculations in a relatively short period of time. Thus, it has become possible to employ optimization methods during the design of different technical objects in the variety of engineering scopes and Industries, even when calculations require large computational resources (structural, thermal, and gasdynamics or hydrodynamics calculations). The efficiency and practical value of the optimization methods employment in various areas (for example, turbomachinery) has already been demonstrated by different authors including ourselves in dozens of papers and at well-known forums and conferences [1], [2], [3].

During the optimization process a designer may have to vary more than a hundred design variables and constraints. Therefore the procedure of preparing the initial data for optimization may take a long time. The problem of the inconsistencies of parameterized geometry and mesh as well as their coupling may appear. For the successful automatic optimization cycle of 2D hydrofoil design we utilized IOSO optimization procedures that were automatically coupled with geometry parameterization (linking with mesh construction). The user-friendly automatic implementation of CFD solver launching was also handled via IOSO procedures.

In this paper we provide an introduction to the method and some results of 2D hydrofoil optimization design tasks "with cavitation free" and "cavitation on" parameters of external water flow.

The goal of this paper is to show the possibility as well as the theoretical and practical value of the employment of optimization methods while designing hydrofoils or their elements. The results have qualitative character; there was no validation with experimental data. These results do not contradict the existing published data for 2D hydrofoil experiments and simulation.

1. INTRODUCTION

Lately there have been many papers published concerning different aspects of 2D hydrofoil design and its behavior under different conditions of external water flow. These works were based on theoretical investigations or experiment measurements as well as numerical simulations.

Good qualitative (and in many cases quantitative) correlations were achieved between experimental data and numerical simulations even for multiphase (cavitation) cases. Investigators used different parameters of simulation (turbulence models, cavitation models, mesh parameters and so on) and some of them made comparative analysis of the influence of simulation parameters on the results of simulation [4], [5], [6], [7].

Some authors offered some point methods and recommendations for the improvement of the behavior and hydrodynamic parameters of 2D hydrofoils.

But we almost haven't encountered the proposals of using design optimization methods or technologies for improving 2D hydrofoil geometry in automatic manner. We believe that our proposal of such a method might be used for the research of 2D hydrofoil behavior and could widen the boundaries and the scope of today's investigations as well as help making investigations more universal and easier in some respect.

The proposed automatic optimization procedure consists of several points: 1) we need to prepare parameterized geometry for the object under consideration (we used CAD software to do that) 2) we need to perform automatic mesh building based on the new geometry. This is so-called mesh-geometry translation (we used ANSYS Icem CFD as a mesher) 3) we need to launch CFD-solver and automatically analyze new results (we used ANSYS CFX as CFD solver) 4) we need to use optimizer and project integration tool to automatically link these processes into a project optimization cycle (we used IOSO NM software for this purpose)

2. FEATURES OF THE IOSO TECHNOLOGY ALGORITHMS

The multi-objective optimization problem minimizes a vector of m objective functions, namely

$$\min_{\bar{x}\in D} \tilde{y}_i(\bar{x}) \quad for \quad i=\overline{1,m}\,. \tag{1}$$

A correct multi-objective problem formulation is possible on the basis of the optimality concept. In most technical multi-objective problems, the Pareto-optimality concept is used [8]. According to this concept vector, $\bar{x}^p$ - is Pareto-optimal ($\bar{x}^p \in P$) if $\bar{x}^p \in D$ and there does not exist such $\bar{x}\in D$, that $\tilde{y}_i(\bar{x}) \le \tilde{y}_i(\bar{x}^p), \forall\, i=\overline{1,m}$ even if one of these inequalities is strict. In this case, the multi-objective optimization problem involves finding a full set of Pareto-optimal points.

As a rule, it is impossible to find the full infinite set of Pareto-optimal points when solving realistic problems. For this reason the engineering statement of a multi-objective problem consists of finding a finite subset of criteria-distinguishable Pareto-optimal points. Thus, it is required to find all the elements of the set $A \in P$, such that for any two vectors $\bar{x}_j \in A$ and $\bar{x}_k \in A$:

$$\sum_{i=1}^{m}\left|\tilde{y}_i\left(\bar{x}_j\right)-\tilde{y}_i\left(\bar{x}_k\right)\right| > \varepsilon,\; j\neq k \tag{2}$$

The parameter ε of the Pareto-optimal points distinguishability is specified by the designer. The number of distinguishable Pareto-optimal points depends on the value of the distinguishability parameter ε and topology of the goal functions and constraints.

Every iteration of the IOSO algorithm consists of two steps [9]. The first step is the creation of analytical approximations of the objective functions. Our approach is based on the widespread application of the response surface technique, which depends upon the original approximation concept. According to this concept we use adaptively global or middle-range, multi-point approximation. One of the advantages of our approach is the possibility of ensuring good approximating capabilities using the minimum amount of available information. This possibility is based on self-organization and evolutionary modeling concepts [10]. During the approximation, the approximation function structure is being evolutionarily changed, so that it allows for the successful approximation of the goal functions and constraints to have sufficiently complex topology.

As a rule, it is impossible to correctly specify the parameter of Pareto-optimal points distinguishability, ε, from the beginning. For this reason the designer specifies the desired number of Pareto-optimal points, and the parameter ε is adaptively changed during optimization to achieve this desired number of solutions uniformly distributed in objectives space.

The main advantages of this algorithm over traditional mathematical programming approaches are the following:

- convolution approaches are not used in solving multi-objective problems;
- the algorithms determine the desired number of Pareto-optimal solutions, so that these solutions are uniformly distributed in the space of objectives;
- it is possible to solve the optimization problems for the objective functions of complex topology: non-convex, non-differentiable, with many local optima;
- it is possible to naturally employ the parallelization of the computational process.

These advantages are the basis for the wide use of the various modifications of this method in the real-life problems.

The software and tools of the IOSO Technology consist of several independent algorithms. IOSO technology algorithms are practically insensitive with respect to the types of objective function and constraints: smooth, non-differentiable, stochastic, with multiple optima, with the portions of the design space where the objective functions and constraints could not be evaluated at all, with the objective function and constraints dependent on mixed variables, etc.

The flexible structure of IOSO main algorithm provides wide opportunities for the development of new approaches aimed at the reduction of the computing time for complex real-life problems [11].

3. OPTIMIZATION OF HYDRODYNAMIC CHARACTERISTICS OF 2D HYDROFOIL

3.1 FLOW AND MODEL PROBLEM STATEMENT

At certain cavitation numbers that is for certain velocities and pressures of external water flow, vapor caverns appear on the surface of hydrofoil. This phenomenon is called cavitation and considerably influences hydrofoil hydrodynamic parameters.

It is well-known that for some temperature of external water flow the key parameters of this flow are the Reynolds number, Re, and the cavitation number, σ.

$$Re = \rho U_\infty l/\mu \tag{3}$$

$$\sigma = (P_\infty - P_v)/((1/2)*\rho U_\infty^2) \tag{4}$$

where ρ – flow density at inlet, U_∞ - inlet velocity, l – chord length of a hydrofoil, μ - flow dynamic viscosity, P_∞ - inlet pressure, P_v – saturation pressure

The Reynolds number determines the flow properties and the cavitation number determines the appearance of cavity caverns on hydrofoil. From these formulas we can see that pressure does not influence the Re number (we neglect the influences on dynamic viscosity and density) and the influence of velocity is linear in the case of the Re number and has inverse square law in the case of the cavitation number. Keeping this in mind for our work we see that for the qualitative assessments of the influence of cavitation phenomenon on hydrofoil hydrodynamics, the cavitation number is the key parameter and could be changed via pressure at inlet. For our tasks we chose two values of the cavitation number (two inlet pressures): one when the cavitation is absent (for this case we switched off the cavitation model in the CFD solver) and the other when the cavitation is present $\sigma = 0.99975$ (for this case we switched on the cavitation model in the CFD solver).

Other flow parameters and model settings were as follows:
velocity flow $U_\infty = 8$ m/s, water temperature = 293 K, saturation pressure $P_v = 2343$ Pa
We used Rayleigh Plesset Model [12] with saturation pressure criterion, we chose homogeneous model and describe all phases as continuous fluids (other cavitation model parameters in CFX where left at default values), turbulence model - k-e.

3.2 GEOMETRY PARAMETERIZATION

The problem of the adequate parameterization of geometry is one of the most important problems engineers encounter when solving design optimization tasks. For example, poor parameterization may lead to bad results because of infeasibility of theoretically optimal geometry forms. Bad geometry resolution may result in poor quality and non-robust properties of solution.

We used our own approach to the parameterization of a hydrofoil shown on the Fig.1

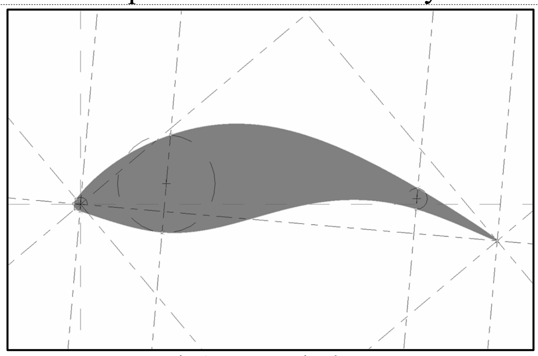

Fig 1 Parameterized geometry

We used two fixed constraints for geometry: chord of hydrofoil l = 0.3 m and angle of attack = 5 grad. Geometry parameterization was accomplished using 7 independent variable parameters. We formed the profile of a hydrofoil using splines that have tangent connections. This geometry representation features two independent focuses of curvature in the leading and trailing edges.

We used our own approach to parameterization other than some existent standard approaches because of several reasons: firstly, different countries use their different standards for foil parameterization, secondly as we will see from our results later, standard foil parameterization could be insufficient for our research especially in the case of “cavitation on” tasks where we obtained very untypical geometry forms as results.

The other difficulty connected with geometry parameterization could arise when during automatic geometry parameter changes there appear geometry inconsistencies and geometry rebuilding crashes. That is why we need to employ quite robust optimization methods which are sustainable to the model crashes during optimization, IOSO optimization methods meat this requirement.

3.3 MESH RECONSTRUCTION

We used fully hexahedral mesh with boundary layer resolution. First time it was built “by hands” than was associated with the parameterized geometry and was rebuilt automatically every optimization iteration. The mesher should also answer several requirements one of which is that it should support automatic script-regime. We used ANSYS Icem CFD which satisfies all our needs. Fig 2 presents some meshes that were automatically constructed during optimization process.

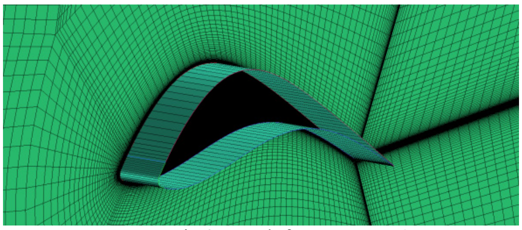

Fig 2a Mesh for geometry 1

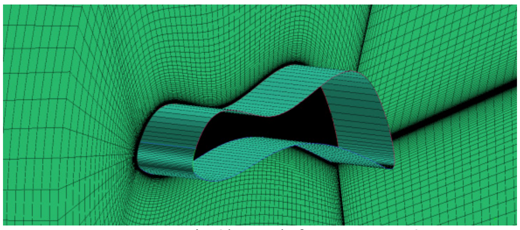

Fig 2b Mesh for geometry 2

3.4 CFD TASK STATEMENT

To successfully solve 2D task for both "cavitation free" and "cavitation on" cases the following conditions were set: inlet velocity boundary condition at inlet, outlet static pressure boundary condition at outlet, 2D symmetry plane boundaries.

For the "cavitation free" we solved steady state task. There were used high resolution advection scheme when the convergence criteria was set 1.E-4.

We had to decide whether to use the steady state or transient solution for "cavitation on" case. We made test analyses comparing the results of steady state and transient task solutions for several geometries and found that not enough convergence was achieved for the steady state task and we had some instability of the force values (oscillations) on hydrofoil. Figs 3 and 4 show the behavior of the parameter pressure normal force Y on hydrofoil in steady state and transient cases respectively in "cavitation on" regime.

Based on our findings we chose transient task statement for our work for "cavitation on" tasks. We used averaged in time values of the forces acting on the hydrofoil. We also used high resolution advection scheme. For transient scheme we chose second order backward Euler option and for convergence control we set maximum coefficient loops equals 10.

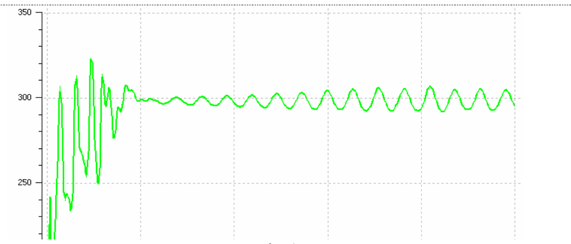

Fig 3
pressure normal force Y on the hydrofoil (steady state solution)
cavitation is on

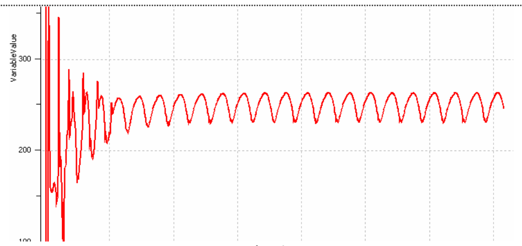

Fig 4
pressure normal force Y on the hydrofoil (transient solution)
cavitation is on

3.5 OPTIMIZATION PROBLEM STATEMENT

1. Two-objective optimization task for simultaneous maximization of lift force Fy and minimization of drag force Fx on a hydrofoil (cavitation is off) is stated
   a. On the basis of previous task two-objective optimization task is stated for simultaneous maximization of hydrodynamic quality Fy/Fx and maximization of lift force Fy. (cavitation is off)
2. Two-objective optimization task for simultaneous maximization of lift force Fy and minimization of drag force Fx on a hydrofoil (cavitation is on) is stated
   a. On the basis of previous task two-objective optimization task is stated for simultaneous maximization of hydrodynamic quality Fy/Fx and maximization of lift force Fy. (cavitation is on)

In all the tasks we used 7 independent design optimization parameters (7 independent geometry parameters that describe the geometry profile of the hydrofoil)

3.6 MAIN RESULTS

1. Two-objective optimization task for simultaneous maximization of lift force Fy and minimization of drag force Fx on a hydrofoil (cavitation is off) is stated. Fig 5 shows a Pareto set of optimal solutions (optimal geometries) after 500 analysis calls:

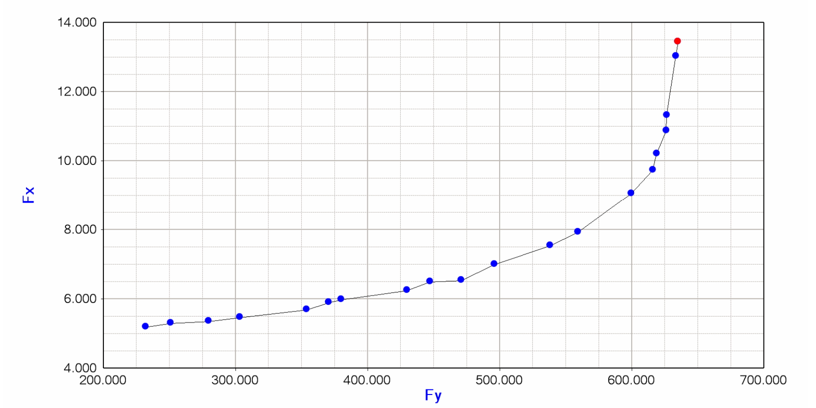

Fig 5 Pareto Set
Fy – maximize, Fx – minimize

Fx compromise lies in the bounds **from 5 to 13.5**
Fy compromise lies in the bounds **from 232 to 635**

Figs 6 and 7 show the geometries for the margin Pareto points from Fig 5:

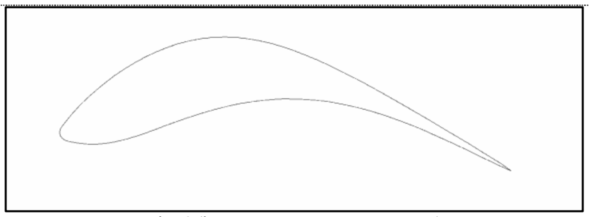

Fig 6 (best Fy, worst Fx geometry)

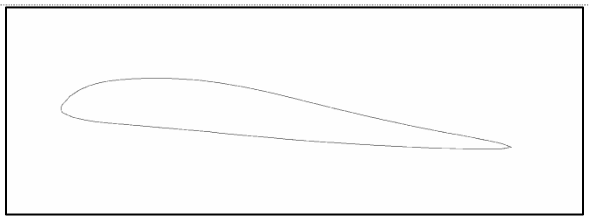

Fig 7 (worst Fy, best Fx geometry)

We can see that these geometries have quite typical forms for "cavitation free" case. Figs 8-11 present the results in terms of vector velocity and pressure plots for the same geometries.

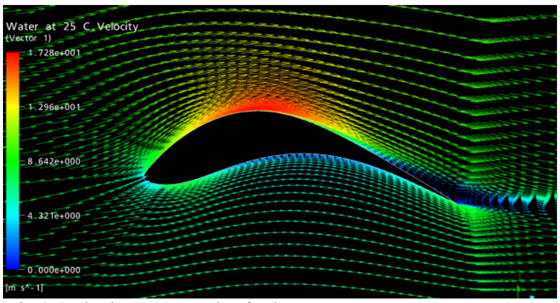

Fig 8 (velocity vectors plot for best Fy, worst Fx geometry)

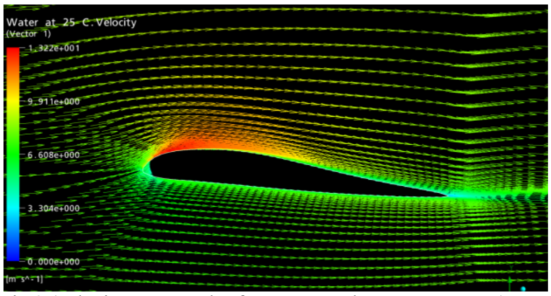

Fig 9 (velocity vectors plot for worst Fy, best Fx geometry)

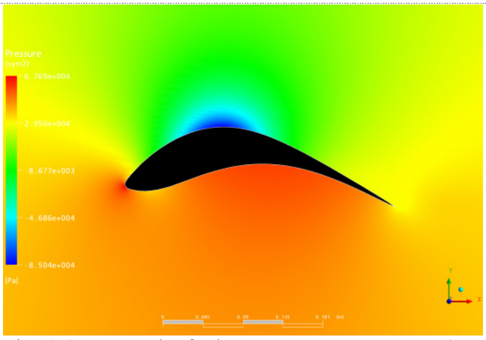
Fig 10 (pressure plot for best Fy, worst Fx geometry)

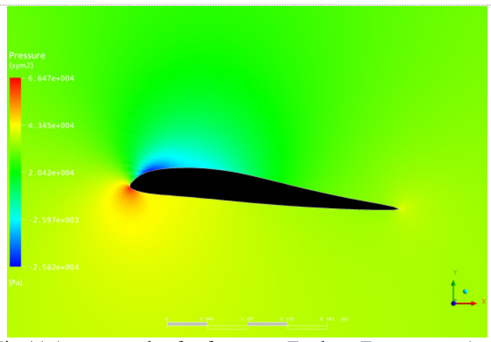
Fig 11 (pressure plot for for worst Fy, best Fx geometry)

1a. On the basis of previous task two-objective optimization task is stated for simultaneous maximization of hydrodynamic quality Fy/Fx and maximization of lift force Fy. (cavitation is off). Fig 12 shows Pareto set of optimal solutions (optimal geometries) after additional 100 analysis calls:

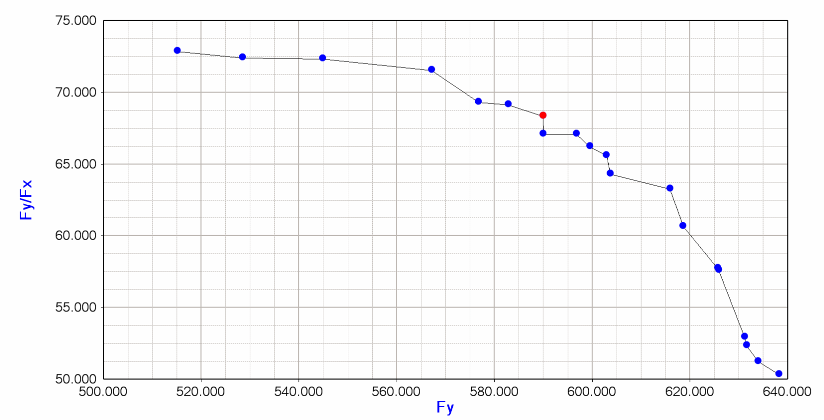

Fig 12 Pareto Set
Fy/Fx – maximize, Fy – Maximize

Fy/Fx compromise lies in the bounds **from 50 to 73**
Fy compromise lies in the bounds **from 515 to 640**

The point of maximum Fy in Fig 12 corresponds to the same point on Fig 5 of the previous task 1. Figs 13 and 14 show the geometries for points of the best hydrodynamic quality Fy/Fx and some intermediate (which we call optimal) point of the Pareto set marked with red color in Fig 12.

Geometry results:

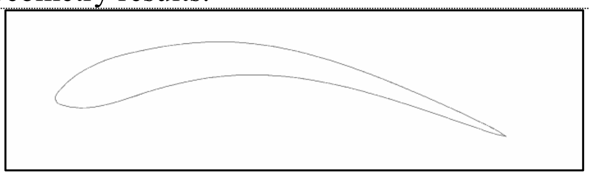
Fig 13 (best Fy/Fx geometry)

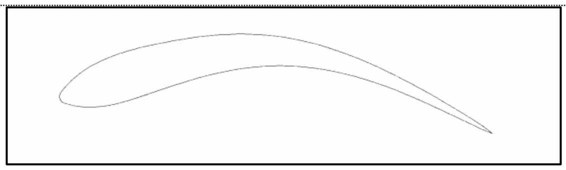
Fig 14 (optim Fy/Fx, optim Fy geometry)

2. Two-objective optimization task for simultaneous maximization of lift force Fy and minimization of drag force Fx on a hydrofoil (cavitation is on) is stated. Fig 15 shows a Pareto set of optimal solutions (optimal geometries) after 500 analysis calls:

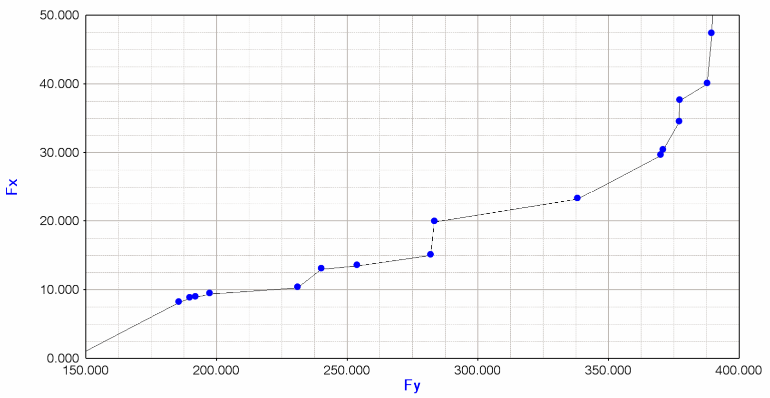

Fig 15 Pareto Set
Fy –maximize, Fx – minimize (cavitation is On)

Fx compromise lies in the bounds **from 8 to 48**
Fy compromise lies in the bounds **from 180 to 380**

Figs 16 and 17 show the geometries for the margin Pareto points from Fig 15:

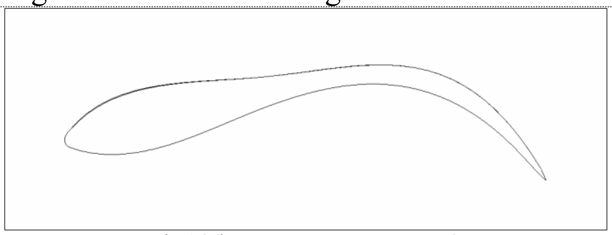

Fig 16 (best Fy, worst Fx geometry)

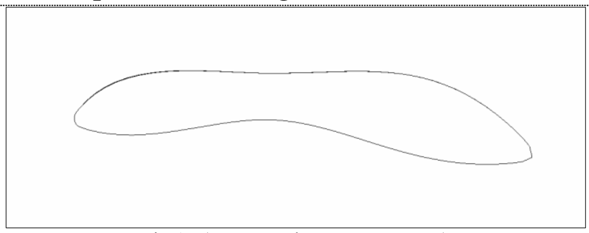

Fig 17 (worst Fy, best Fx geometry)

One can see that resulted geometries have quite untypical form and are sufficiently different from the case of cavitation free optimization task. Specifically, these geometries feature some hollows on the suction sides of the hydrofoil profile.

Figs 18-21 show some results in terms of VOF, velocity vector plots for these geometries.

Fig 18 (VOF plot for best Fy, worst Fx geometry)

Fig 19 (VOF plot for worst Fy, best Fx geometry)

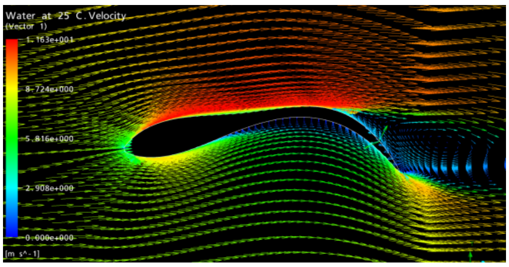

Fig 20 (velocity vectors plot for best Fy, worst Fx geometry)

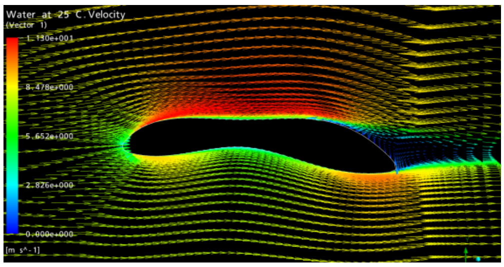

Fig 21 (velocity vectors plot for worst Fy, best Fx geometry)

2a. On the basis of previous task two-objective optimization task is stated for simultaneous maximization of hydrodynamic quality Fy/Fx and maximization of lift force Fy (cavitation is on). In Fig 22 one can see a Pareto set of optimal solutions (optimal geometries) after additional 200 analysis calls:

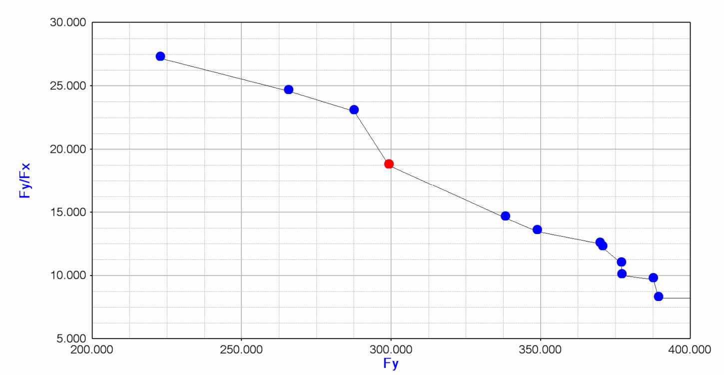

Fig 22 Pareto Set
Fy/Fx –maximize, Fy – maximize (cavitation is On)

Fy/Fx compromise lies in the bounds **from 7 to 27**
Fy compromise lies in the bounds **from 220 to 380**

The point of maximum Fy in Fig 22 corresponds to the same point in Fig 15 of the previous task 2. Figs 23 and 24 show the results for points of the best hydrodynamic quality Fy/Fx and some intermediate (which we call optimal) point of the Pareto set marked with red color in Fig 22.

Geometry results:

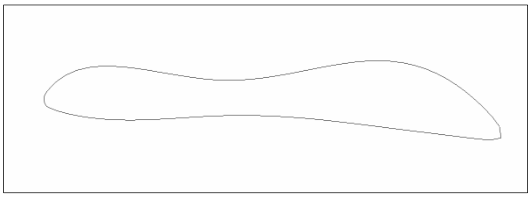

Fig 23 (best Fy/Fx geometry)

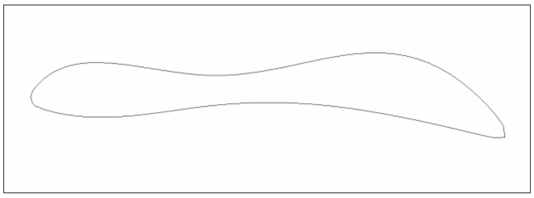

Fig 24 (optim Fy/Fx, optim Fy geometry)

Some vector velocity and VOF plot results:

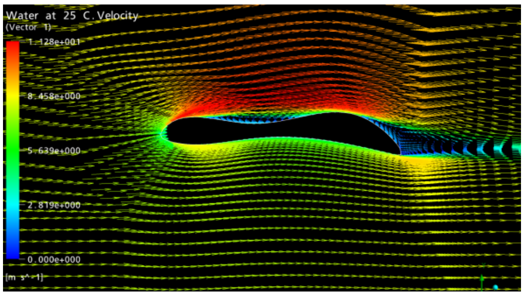

Fig 25 (velocity vectors plot for optim Fy/Fx, optim Fy geometry)

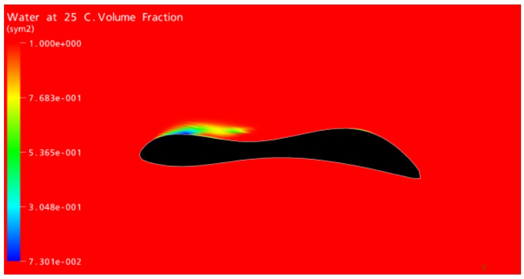

Fig 26 (VOF plot for optim Fy/Fx, optim Fy geometry)

For all the simulations parameter Yplus on the surface of hydrofoil lies in the bounds of 1 to 100.

From the comparison of the results of optimization tasks for “cavitation free” and “cavitation on” cases, we can make an assumption why in “cavitation on” case we have geometries with some hollows on the suction sides. These hollows are occupied by cavitation caverns and thus provide some integrity of the hydrofoil profile while flow either does not separate or separates and reattaches on the suction side of the hydrofoil surface.

As a summary, let us mention that such untypical hydrofoil geometries in the cases of optimization tasks with cavitation on were obtained due to our initial parameterization of the hydrofoil geometry with two independent focuses of curvature in the leading and trailing edges of it (see Fig 1).

4. CONCLUSION:

This work and qualitative results showed an implementation of a modern method employing the optimization technology linked with CAD, Mesh and CFD software for fully automatic design of hydrofoils. The results demonstrate considerably different optimized forms of hydrofoils for “cavitation free” and “cavitation on” external water flows. We believe that such a method could be used not only for the design of hydrofoils, but for the research in general, while providing the expanded space of possible solutions and parameter behavior for investigators.

5. AKNOLEGEMENTS

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