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Приклади та успішні результати міждисциплінарних досліджень у гідродинаміці

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Анотація: *Досвід міждисциплінарних досліджень у Лабораторії охоплює зв'язки біології з гідродинамікою та гідродинаміки з фізикою плазми. Біологія поділилася з інженерією прототипом та деякими механізмами оптимального руху в середовищі. Це стосується властивостей шкіри швидкохідних морських тварин, ретельно відшліфованих еволюцією, що дозволило вченим розробити спеціальні покриття для зниження опору. Співпраця гідродинаміків з фізиками плазми призвела до розробки нового приладу для активного керування потоком, який показав себе ємним та енергоефективним.*
Ключові слова: *біологія, гідродинаміка та фізика плазми; активне керування потоком; багатопараметричні дослідження.*

EXAMPLES AND SUCCESSFUL OUTCOMES OF MULTI-DISCIPLINARY RESEARCH IN FLUID DYNAMICS

Experience in multidisciplinary research in the Laboratory embraces couplings of biology with fluid dynamics and fluid dynamics with plasma physics. The biology shared with engineering a prototype and some mechanisms of optimal moving in fluids. These were skin properties of high-speed marine creatures thoroughly polished by evolution which enabled scientists to develop special coatings to reduce drag. The cooperation of fluid dynamicists with plasma physicists resulted in the development of a new instrument for active flow control which showed itself smart and energy-efficient.
Keywords: biology, fluid dynamics, and plasma physics; active flow control; multi-parameter research.

1. Biological prototypes and aerodynamic solutions

Evolution-optimized features of living systems have long ago become attractive for engineers in terms of their copying and applications in technology. Skin-flow interaction of high-speed marine

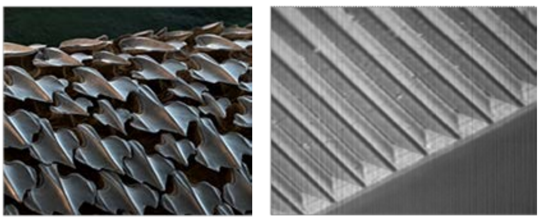

Fig. 1. Surface streamwise structure: shark scale (a) and mechanical riblets (b) [1]

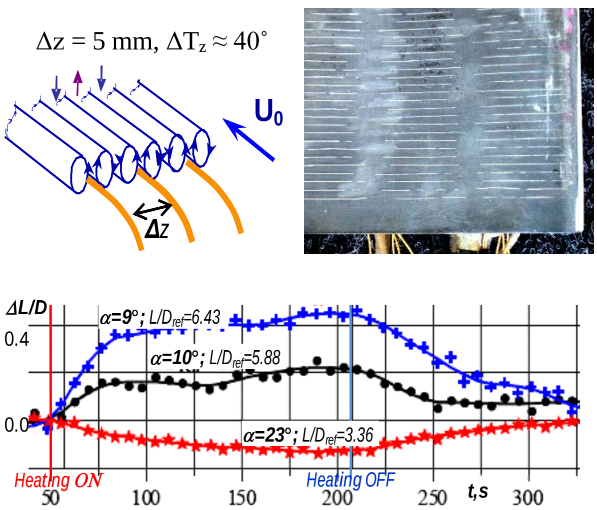

Fig. 2. Increments of lift-to-drag ratio ΔL/D *vs* time for near-critical and supercritical angles of attack

creatures is one of the points of interest that was used to develop riblet coatings (Fig. 1, a, b) which are proven to improve aerodynamic performance [1, 2]. Our development of this idea was implemented in a form of the so-called virtual thermal riblets [3, 5] (Fig. 2).

In experiments, such a rib-like structure was realized as a flush-mounted array of streamwise electrically heated elements. This step turned passive flow control by mechanical riblets into active flow control using “thermal riblets” which enable to variation of a regular temperature gradient across the surface in a process of operation. Measured lift and drag coefficients of a model reveal a possibility to improve the aerodynamic performance before the stall, i.e. for near-critical angles of attack shown in Fig. 2.

A greater favorable impact can be obtained with the spanwise array of plasma discharges applied instead of the array of resistively heated longitudinal elements embedded into the model [6, 7]. Plasma-assisted flow control opens new advantages of the developed technique:

- It enables active and remote flow control depending on a way of energy deposition to plasma actuators;
- The control factor is applied directly to the flow maintaining the surface smooth;
- A broad number of electromagnetically controlled parameters (intensity, frequency, duty cycle) make a method more flexible and versatile;
- A possibility to optimize the generated vortical structure in accordance with current flow conditions.

2. Combining aerodynamics and plasma physics

Energy deposition to the arrays of plasma discharges can be organized in different ways but all of them require the contribution of professional plasma physicists both to find an elegant engineering solution and to determine a basic mechanism of plasma impact on the flow.

Figures 3 and 4 show the generation of plasma discharges using the microwave (MW) and high-voltage plasma actuation. MW plasma generation is realized using ring-type actuators; the discharge takes place between the tips of an open loop mounted inside a model (left column of Fig. 3). In the flow absence, the discharge stays stable and symmetric (middle column of Fig. 3); at 25 m/s the discharges deform and behave unstably like a candle flame (right column of Fig. 3). It can be eliminated due to higher energy deposited in the flow, e.g. increasing the pulse duration. However, the general behavior of discharges and their impact on the flow has a fluctuating character because of the nonuniformity of the MW field along the array caused by multiple reflections in the test section.

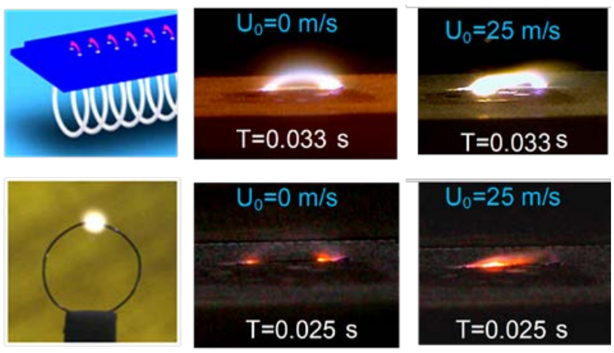

Fig. 3. Quality (temperature) of single plasma discharges depending on free-stream velocity and MW-pulse duration, MW power P_{MW}=1.2 KW

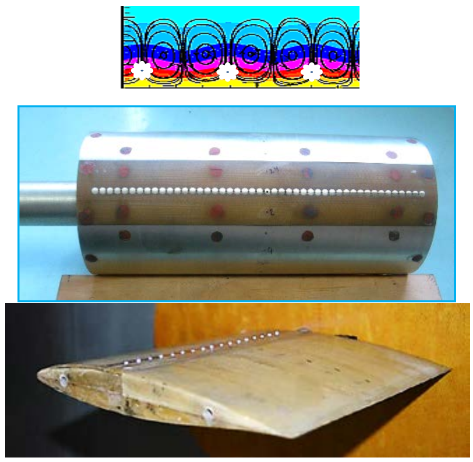

Fig. 4. A circular cylinder (top) and a supercritical airfoil (bottom) with arrays of multi-discharge plasma arrays.

High-voltage plasma discharges are free from this drawback but the nature of their impact on the flow is not as obvious as in the case of MW plasma. Since MW frequencies are incomparable with those of the flow, the temperature factor is believed to be a basic mechanism of their influence on the flow. Another advantage of the MW plasma actuation is the possibility of its remote operation which can be important in the installation of the plasma system on moving or rotating objects.

3. Determination of the impact on the flow

To minimize energy consumption for plasma-assisted flow control, pulsating modes of MW radiation were used. Aerodynamic numerical modeling helped to choose optimal values of pulsation parameters (MW pulse duration τ and repetition rate F). Figure 5 shows patterns of longitudinal vorticity at consecutive moments downstream of the MW-initiated plasma array [4]. Under conditions of correctly chosen pulse parameters, thermal wakes generated by subsequent pulses merge resulting in a regular vortical structure propagating downstream.

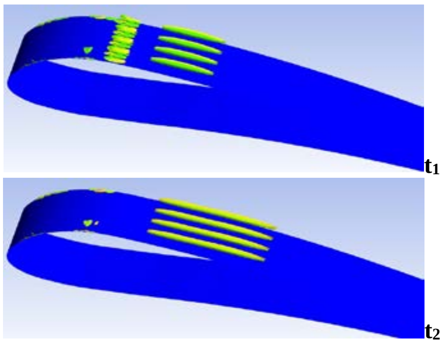

Fig. 5. Development of longitudinal vorticity at a pulsed mode of plasma discharges: U_0=20 m/s, α=5°, τ=100μs, F=1000 Hz

An adequate flow response to the scale of introduced disturbances supposes certain sustainability of the organized structure and its impact on integral flow characteristics.

The measure of plasma impact on the flow is found from the variation of the aerodynamic performance, lift and drag coefficients (Fig. 6). The conclusions are verified using analysis of the pressure field redistribution around a model as well as due to the numerical analysis of flow fields over controlled models.

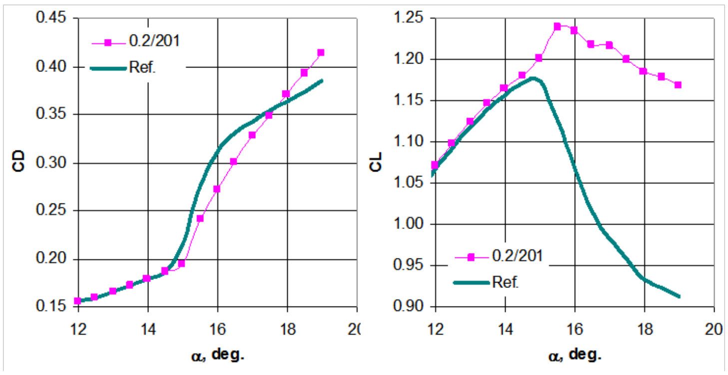

Fig. 6. Drag and lift coefficients of airfoil model controlled by arrays of pulsating plasma discharges: $Re_x = 5x10^5$; F=200 Hz; τ=150 μs, distance between the neighboring discharges, Δz=10 mm

4. Conclusion

The concept of smart energy-efficient flow control is formulated due to ideas brought from biological investigations. Having motivated the engineering modeling, they enabled to develop a number of efficient techniques of active flow control validated numerically and experimentally. The techniques are based on the generation of a spanwise flow regularity of a thermal or any other nature. In particular, application of spanwise arrays of plasma discharges initiated either with the MW field or using a high-voltage generator was possible due to the collaboration with plasma physicists. Thus, the multidisciplinary approach to the research organization demonstrated the shortest and most efficient way to the goal of drag reduction with the simultaneous raise of lift.

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