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IMPROVEMENT OF AERODYNAMIC PERFORMANCE USING THERMAL FIELDS OF LOCALIZED PLASMA SOURCES

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ABSTRACT

Matched numerical and experimental studies are performed in the framework of the developed flow-control concept based on generation of small spanwise-regular disturbances. The idea arose from the analysis of skin-flow interaction of high-speed marine animals. In practice, flow regularity of a given scale is introduced as a temperature boundary condition, T(z). Experimentally, it is realized with spanwise arrays of thermal sources, in particular, in a form of localized plasma discharges generated in a field of microwave radiation. Measured aerodynamic coefficients are shown to correlate with the induced streamwise vortical structure of a boundary layer.

INTRODUCTION

High speeds of marine animals and their good orientation are of a special interest to engineers since the evolution must have developed optimal systems and functions to move in fluid. Relevant bionic studies explained these features with optimized skin-flow interaction. It takes place due to the evolution-created spanwise-regular skin structure of high-speed marine animals (dolphins, sharks, tuna, etc.), the more orderly, the faster a species is. That is why their skin properties were exhaustively studied and served as a prototype for engineering solutions, e.g. in a form of riblets (Figure 1).

Looking for prototypes in Nature, it is reasonable to suppose that the skin structure should mirror the flow structure so that to provide more comfortable motion, e.g. consuming least energy and reducing the perception of pressure fluctuations in the vicinity of a body surface. In engineering terms, the whole skin-flow system operates like a modern active flow-control system with a sensor-based feedback. From the modeling viewpoint, the organized fluid motion in a boundary layer has a definite impact on mechanisms of fluid transport near a wall and thus on integral flow characteristics. The latter gives a reason and a basis for concepts of optimized flow control.

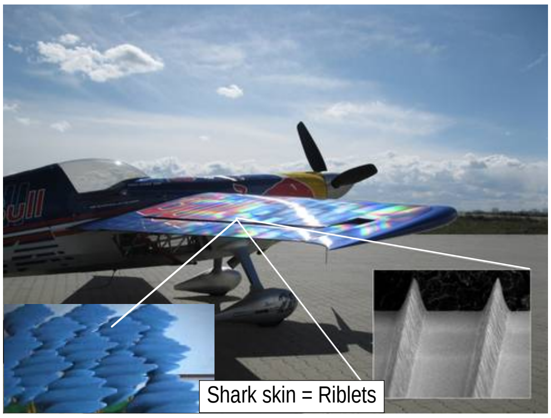

Figure 1 Riblet-type surface in nature and in engineering

Boundary-layer flows are known to be predisposed to natural formation of streamwise counter-rotating vortices [1-3, 5, 6], this fact must have had an impact on the evolutionary developed morphology of outer skin layers of creatures moving in fluid. They are an intrinsic flow structure element of [1]

- laminar-turbulent boundary layers;
- boundary layers affected by body forces (over heated and curved surfaces);
- turbulent spot periphery in a form of a “fringe” of streamwise vortices;
- sublayers of turbulent boundary layers;
- rotating flows, e.g. those in a gap between concentric cylinders (Taylor vortices);
- secondary flows in curved channels and river-beds;
- MHD flows with imposed transverse magnetic fields;
- Langmuir circulation in ocean.

A universal form of this fluid motion supposes similar mechanisms of its development as well as similar approaches to its control. Learning from nature and getting an insight into physical mechanisms of the involved processes is an efficient way to design optimal systems. In the engineering practice, such a design is to be based on general principles of flow self-organization and on the present day technologies, e.g. like those of plasma.

NOMENCLATURE

c_x	[-]	Drag coefficient
c_y	[-]	Lift coefficient
f	[s^{-1}]	Repetition rate of electromagnetic pulses
G	[-]	Goertler number, G= $G = U_0\delta_2^{3/2}\nu^{-1}R^{-1/2}$
R	[m]	Radius of surface curvature
Re	[-]	Reynolds number, Re= $U_0 x\nu^{-1}$
T	[C]	Local surface/flow temperature
ΔT	[C]	Temperature difference along λ_z
U_0	[m]	Free-stream velocity
x, y, z	[m]	Streamwise, normal and spanwise coordinate axes

Special characters

α	[°]	Angle of attack of a test model
λ_z	[m]	Spanwise distance between thermal sources
δ_2	[m]	Boundary-layer displacement thickness
ε	[-]	Free-stream turbulence level
ν	[m^2s^{-1}]	Kinematic viscosity
τ	[s]	Electromagnetic pulse duration

PROPERTIES OF STREAMWISE VORTICES

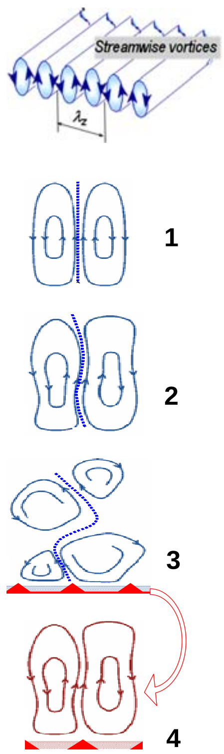

Figure 2. Downstream growth, breakdown and maintenance of streamwise vortices

Formation and behavior of streamwise vortices is described mathematically correctly in the framework of the Goertler instability theory [1, 2] applied to boundary layers over concave surfaces. In the framework of the developed flow control concept, it is used as a mathematical background and a reference in choosing scales of initiated and maintained streamwise vortices (Figure 2, top). Energizing inherent to flow vortices of a certain scale λ_z, one can manipulate processes in near-wall flows either delaying laminar-turbulent transition or enhancing mixing that depends on chosen vortical scales correlated with basic flow parameters.

Natural evolution of the vortical system in a boundary layer consists of several successive stages of its formation, deformation and breakdown (Figure 2, 1-3). However the lifetime of this organized fluid motion can be extended due to the localized energy release as it is shown schematically in Figure 2,4. For that, various kinds of spanwise-regular disturbers can be like mechanical vortex-generators or localized thermal sources. A key issue here is a spanwise regularity of small disturbances introduced in the near-wall flow [2, 3]. Distributed thermal fields, i.e. selective heating of a boundary layer, have a number of advantages [5-7].

- The surface stays smooth when a control factor (temperature) is applied at estimated moments, locations or modes of operation.
- The control factor intensity and character can be varied within a broad range according to an operation mode and depending on a location of the controlled sections over a body.
- Scales of initiated vortices can be adjusted to the body geometry as well as to current flow conditions.
- Flow control can be optimized due to independent manipulation with individual heated sections over a body.

Since the boundary-layer flows are predisposed to the formation of counter-rotating streamwise vortices, it does not require much energy to maintain such a vertical motion with a scale given by a spanwise distance between neighboring disturbers.

NUMERICAL SIMULATION.
Low-temperature disturbances

Numerical modeling deals with investigations of a fine flow structure modified with z-regular disturbances introduced into the flow by spanwise arrays of thermal sources. It is aimed at guiding experiments and supplementing them in parts where measurements were not possible. Understanding of physical mechanisms and estimation of certain marginal parameters enables to optimize the research work. To get unequivocal information, the simulation is split into two basic tasks: (1) a modeling problem of the boundary-layer over a curved cylindrical surface of a constant radius and (2) an experiment-matching problem of the flow around an airfoil; both are considered in a presence of an array of localized plasma sources.

Calculated components of streamwise vorticity in the framework of Task (1) show that thermal sources generate pairs of streamwise vortices around each source over a concave surface (Figure 3, [2]). Figure 3 shows quite different growth rates of the second and first instability modes, λ_{G2} and λ_{G1},

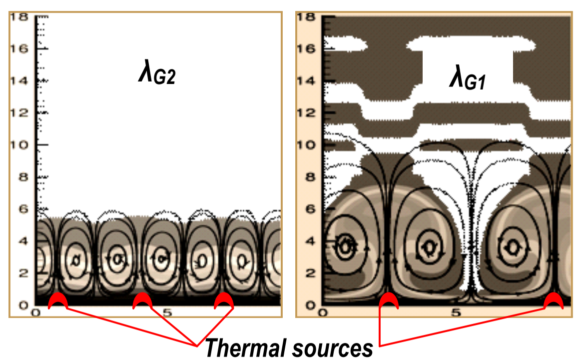

Figure 3 Streamwise vortices of different scales generated with arrays of thermal sources in a transitional boundary layer: G=8; ΔT_z=30° [2]

according to the Goertler theory [1, 2].

The results obtained for flat and convex surfaces without heating (uniform boundary condition) did not show presence of streamwise vortices. But the imposed wavy T(z) boundary condition resulted in the formation of pairs of counter-rotating vortices. Thus the numerical simulation proved feasibility of the developed concept of active flow control based on imposed distributed thermal fields of a given spanwise scale.

High-temperature (plasma) disturbances

The Task (2) related to the flow around an airfoil at various angles of attack was mimicking the situation specified in the experiments: size and geometry of the test model, values of free-stream velocity, angles of attack, parameters of thermal sources (temperature, spanwise step λ_z and downstream location). In practice, spanwise-regular high-temperature disturbances were organized using arrays of ring-type plasma actuators operated in the field of microwave (MW) radiation [4] that is shown schematically in Figure 4.

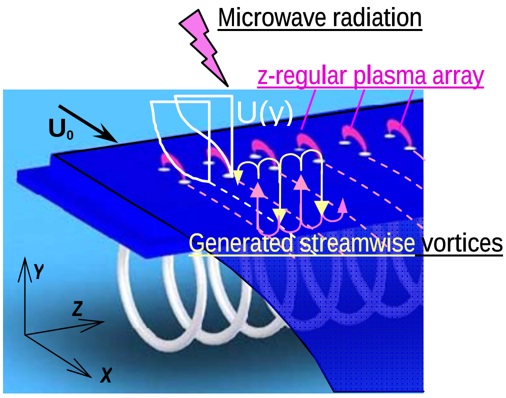

Figure 4. Streamwise vortices generated in a boundary layer with spanwise-regular localized plasma discharges

In case of localized plasma generation, basic control factors are the λ_z distance between the plasma actuators, amplitude characteristics and an operating mode of MW radiation (continuous or pulse).

Following the experiments, a pulse work of the plasma discharges was simulated numerically to display and to analyze features of the flow response to such kind of the boundary layer excitation. It is illustrated schematically in Figure 5.

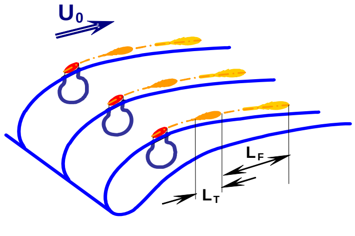

Figure 5. Thermal patterns generated in a boundary layer with pulsed plasma sources, T≈1000°C

The dynamics of temperature distributions in a boundary layer affected by a sequence of MW pulses enables various scenarios depending on pulse mode characteristics, in particular, various extensions of heated areas in the wake, L_T and L_F defined by the pulse duration and repetition rate. Accordingly, the control factor in a form of generated streamwise z-regular vorticity can be optimized with a proper choice of these pulse characteristics. Figure 6 shows calculation results for the pulse mode of thermal excitation with a period T = 1 ms corresponding to the pulse repetition rate f=1000 Hz and the pulse duration τ=100 μs.

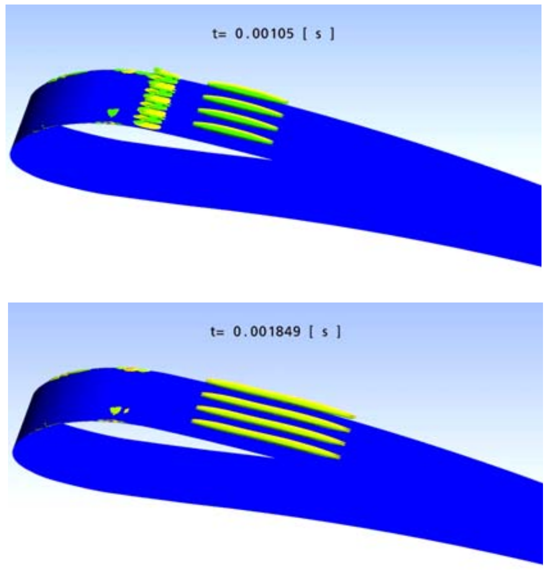

Figure 6. Iso-surfaces of streamwise vorticity (±100 s^{-1}); U_0=20 m/s, α=5°, λ_z=10 mm; pulse characteristics: τ=100 μs, f=1000 Hz

Figure 6 demonstrates propagation of two portions of streamwise vortices successively generated in a boundary layer; they merge downstream that makes the structural pattern similar to the one generated with a constant temperature boundary condition of Figure 3.

It is the encouraging result taking into account temperature rapidly falling down in the discharge wake: properly chosen pulse parameters enable to enhance the thermal effects due to the downstream merge of the vortices with a given scale. At the same time, such pulse operation is the energy saving mode that enables to use low power magnetrons (MW generators). It is an important issue both for the experiment planning and for understanding an impact of small disturbances.

Plasma discharges in the flow attached to the model at small angles of attack initiate vortical patterns similar to those above the concave cylindrical surface. The vortices were found to be more intense and longer living in a laminar rather than in a turbulent flow. Besides, the λ_z=1.33 cm spacing was found to be a spanwise limit for the adequate boundary-layer response with one pair of vortices formed between the thermal sources which maintained the given scale propagating downstream.

EXPERIMENT: WIND-TUNNEL MEASUREMENTS

Wind-tunnel measurements were carried out for the same values of flow and control parameters as those taken for the numerical modeling: $U_0 \approx 10$ m/s, 15 m/s $U_{0III} \approx 20$ m/s; angles of attack of the airfoil model varied within $\alpha = -10° \div 35°$.

Plasma discharges were initiated with microwave radiation in a gap of ring-type actuators shown in Figure 4 [4]. Such systems were mounted on test models (Figure 7) to measure aerodynamic forces in a wind tunnel. Aerodynamic coefficients were obtained depending on the flow parameters (free-stream velocity, angle of attack) for various temperature boundary conditions in conjunction with the flow structure determined numerically.

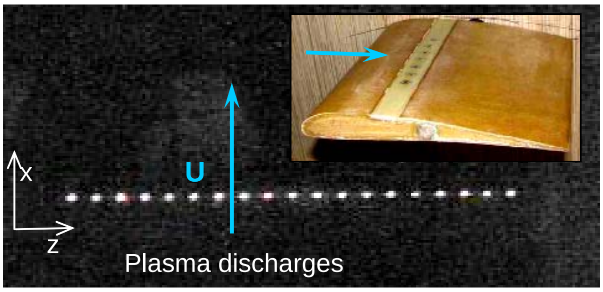

Figure 7. Test model with mounted plasma actuators. Plasma discharges generated over a test model surface during wind-tunnel measurements.

Experiments explicitly displayed the interdisciplinary nature of the investigation where electro- and aerodynamic parts are to be thoroughly matched and studied. Multiple reflections of the radiated electromagnetic wave in the wind-tunnel test section resulted in the extremely nonuniform resultant field. In its turn, it prevented from generation of similar plasma discharges along the model span as it is shown in Figure 8. The situation was aggravated in a process of measurements with a varying angle of attack of the test model.

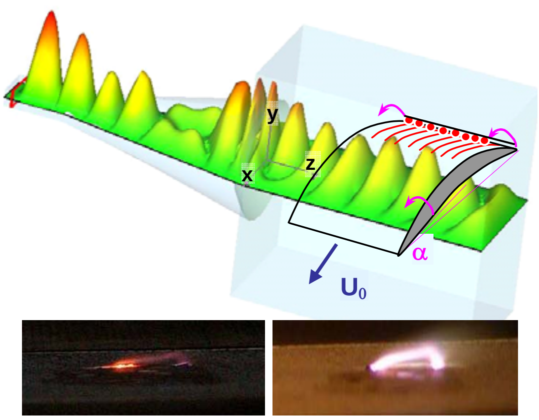

Figure 7. Nonuniformity of MW field and generation of plasma discharges

Eventually the matched electro- and aerodynamic studies enabled to find appropriate engineering solutions to provide correct conditions for measurements of aerodynamic forces. Figure 8 shows an impact of spanwise-regular plasma discharges on aerodynamic coefficients of the model.

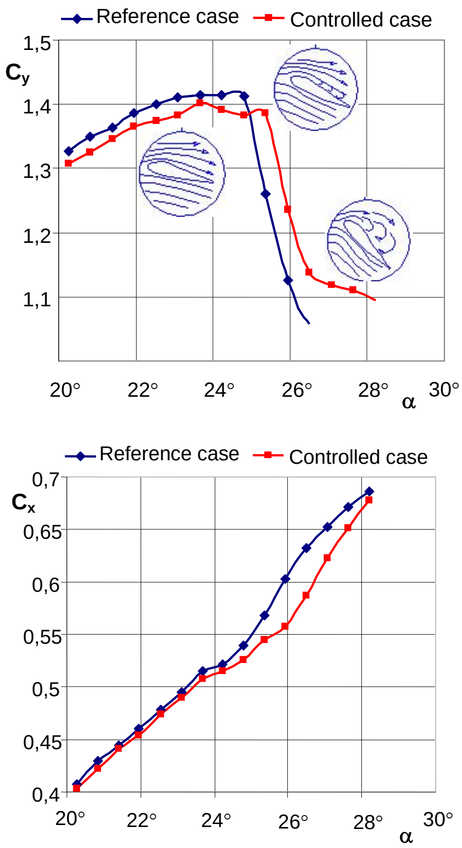

Figure 8. Lift and drag coefficients for various angles of attack of the model, U_0=15 m/s

The obtained measurement results proved that the developed method of boundary-layer control can improve stall characteristics: flow separation delay up to several degrees and lift coefficient growth in over-critical regimes compared to the reference case. In its turn, the delayed boundary-layer separation resulted in reduced drag of the test model. It is in accordance with the numerically shown possibility to maintain the system of streamwise vortices organized due to the imposed thermal fields.

CONCLUSION

- Feasibility is shown of various ways of engineering realization of the developed strategy of flow control using spanwise-regular thermal fields.
- The considered engineering solutions provide a necessary and sufficient number of control parameters for efficient flow control.

- Flow structure purposely modified with the imposed thermal fields studied numerically showed development of streamwise vortices with a given scale.
- Matched experiments showed that the generated vortical structure can essentially change boundary-layer transport properties resulting in increased angles of attack where flow separation occurs and raised lift coefficients at over-critical regimes.
- Advantages of the interdisciplinary research with combined numerical and experimental investigations both in aero- and electro-dynamics are demonstrated.

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