Control of flow characteristics using localized plasma discharges

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The microwave (MW) system was developed for full-scale measurements of aerodynamic characteristics in a wind tunnel. Reliable initiation of plasma discharges was obtained on the airfoil model with 11 initiators over its convex and concave walls at their regular 10-mm spanwise spacing. Experiments showed possibilities to delay flow separation and to raise lift coefficients by 15% together with the drag dropped by 5%. It has proven the developed concept of flow optimization through modification of its turbulent structure and the plasma-control method efficiency.

Nomenclature

c_x	=	drag coefficient
c_y	=	lift coefficient
f	=	repetition frequency of controlled MW pulses
P_{MW}	=	radiation power of MW pulses
R	=	radius of surface curvature
$Re = U_0 x \nu^{-1}$	=	Reynolds number
ε	=	free=stream turbulence level
T	=	local surface temperature
ΔT	=	temperature difference along λ_z
t	=	duration of MW pulses

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U_0	=	free-stream velocity
x, y, z	=	streamwise, normal and spanwise coordinates
α	=	angle of attack of a test model
λ_z	=	spanwise distance between boundary-layer disturbers (here, thermal sources)
ν	=	kinematic viscosity

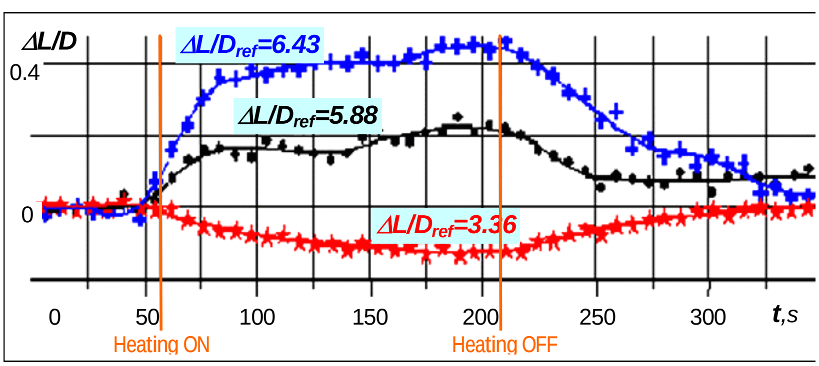
I. Introduction

THIS WORK is a result of concerted efforts of 3 research teams: Institute of Hydromechanics, National Academy of Sciences of Ukraine, National Aviation University of Ukraine and Moscow Radio-Technical Institute, Russian Academy of Sciences. As such, it embraces the fields of fundamental fluid dynamics (Refs. 1, 2) in conjunction with basic electrodynamics (Ref. 5). This multidisciplinary approach arose from the development of a flow control method based on a system of localized plasma discharges initiated with microwave (MW) radiation in a vicinity of a model surface. A physical mechanism underlying this method consists in organization of specific thermal patterns over the surface to initiate formation of boundary-layer disturbances of a given space scale (Refs.1, 3, 4).

The right part of Figure 1 shows schematically the formed thermal array which, in its turn, causes the formation of an organized vortical structure with a given scale λ_z. Pairs of counter-rotating streamwise vortices are known to be an inherent feature of curved boundary-layer flows due to the interaction between viscous and centrifugal forces (Ref. 2). Therefore the thermally imposed spanwise regularity requires the energy deposition only to select and to support a certain space scale of vortices correlated with basic flow parameters rather than to reorganize the whole mode of fluid motion. Since the initiated large-scale vortical structure implies a specific way of fluid transport near a wall, it is expected to modify integral flow characteristics.

The localized energy replenishment to support the organized vortical motion was proposed by means of spanwise-regular heating of the surface with flush-mounted resistive elements (Figure 1, right) or by remote heating of fluid with MW-initiated plasma discharges. The first method was investigated earlier (Refs. 3, 4) having provided a proof of the developed flow control concept in a form of a raised lift-to-drag ratio of the tested airfoil model (Figure 1, left). It encouraged further development of the thermal control approach to provide the research continuity and to improve the functionality and practicalities of the approach, e.g. to enable applications to corrosive fluids as well as to moving or rotating elements and systems like turbine blades.

From an aerodynamic point of view, plasma arrays represent a tool for flow management in a form of spanwise-regular thermal sources with given properties. The whole research is designed as separate but matched aerodynamic and electro-dynamic parts. Flow disturbances are introduced through localized thermal excitation similar to the case of resistively heated arrays mentioned above. Basic control factors are the λ_z distance between the plasma actuators (see Figure 1, Left), their downstream location over a model and amplitude characteristics corresponding to the applied voltage and an operating mode of MW radiation. This kind of applied boundary conditions affects scales and intensity of generated vortices and enables the remote control due to the initiating MW field.



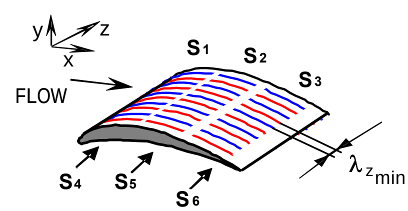


Figure 1. Increments of lift-to-drag ratio ΔL/D *vs* time for near-critical angles of attack for the resistively heated model: α = 9° (black) and 10° (blue) and for a supercritical regime of α = 23° (red), all 6 sections over the model are heated, U_0≈15 m/s, ΔT_z≈40°, λ_z = 5 mm

Numerical simulation of a flow field affected by the array of plasma sources gives an insight into structural features of turbulent boundary layers with embedded large-scale vortices. Plasma discharges are generated at an outer edge of the boundary layer. Numerically obtained information is to prove the method feasibility, efficiency and prospects for flow control.

Experiments required design and construction of a special wind-tunnel facility where operators, the measurement and data acquisition systems are protected from the harmful MW radiation (to simplify experimental arrangements, the wave length was chosen to be 12.5 cm, i.e. most absorbed by water). This aerodynamic complex for multidisciplinary investigations is shown in Figure 2.

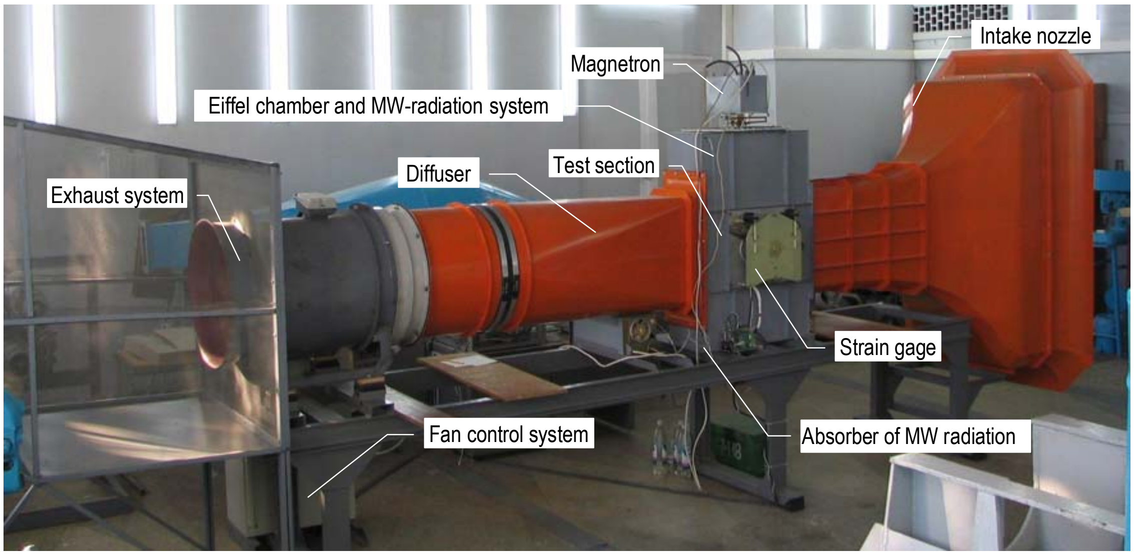


Figure 2. Wind-tunnel facility designed for aerodynamic tests under conditions of MW radiation and plasma generation

II. Results and discussion

The flow control method based on localized plasma generation is a logical development of the concept based on the application of spanwise-organized thermal fields. However due to its remote character, it provides better flexibility of operation compared to the resistive heating of streamwise elements. It is shown schematically in Figure 3.

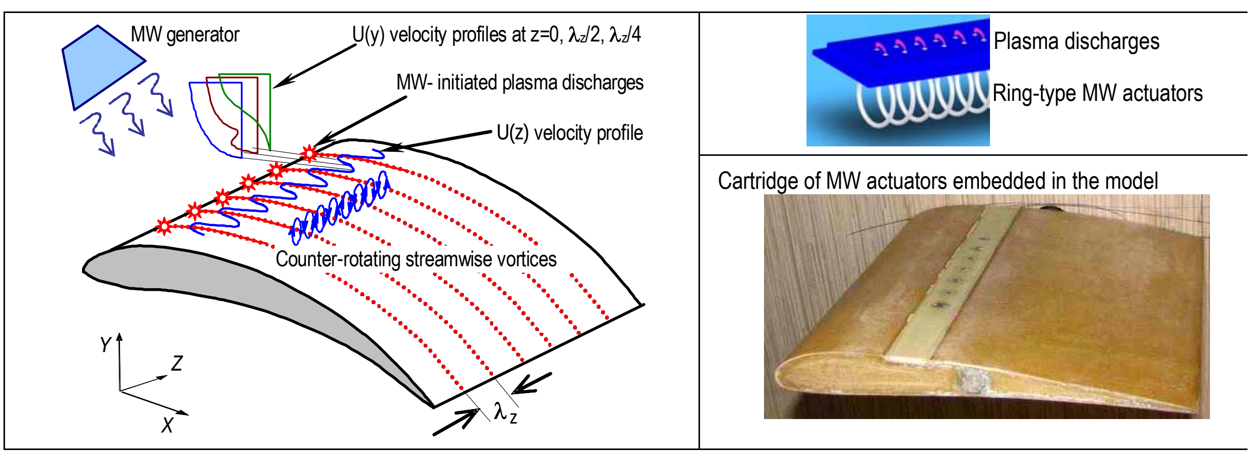


Figure 3. (Right) Problem formulation: flow control based on z-regular temperature boundary condition realized through MW-initiated array of localized plasma discharges with a spanwise scale λ_z of generated vortices (a distance between neighboring plasma actuators). (Left) MW actuators of plasma discharges mounted in the airfoil model.

Basic advantages of the plasma-control approach are as follows.

- It is an active method where selective heating (a control factor) can be switched on and off as needed; it is less inertial compared to the conventional resistive heating; it maintains the surface smooth opposite to methods based on application of any mechanical vortex-generators;
- intensity of the control factor can be varied depending on an operation mode, e.g. on a free-stream velocity or an angle of attack;
- multiple arrays of plasma actuators mounted on a body of complex geometry can provide initiation of vortices of different scales over a body surface,
- energy consumption for flow control can be adjusted to current flow conditions due to variation of radiated MW energy, its duration and frequency characteristics and optimized location of controlled sections over a body.

Thus the research work is aimed at determination of (1) MW radiation parameters which would provide stable generation of discharges and (2) combinations of control and basic flow parameters which would improve the aerodynamic performance of a test model. Having started from the resistive heating, it was applied to the two models of the same span-to-chord size but with different basic downstream curvature tested in a wind tunnel within Re = (1.5-5.0)x10^5. Drag C_x, lift C_y, and pitch moment M_z coefficients were found from measured forces at different values of a free-stream velocity, angles of attack and varying control factors. As a starting point, a case of sustainable vortices generated with λ_z=5 mm was considered for the airfoil-type model with resistive spanwise-regular heating. A possibility was found to increase lift-to-drag ratio by a value of 0.55 as it is shown in Figure 1. This improvement of the model aerodynamics was obtained under very small relative energy consumption required for the control system operation.

The same research algorithm was applied to the plasma-control method. First of all, generation of single and multiple discharges was investigated in a desk-top jet facility of MRTI so that to formulate recommendations on MW radiation system designed for the wind tunnel. Figure 4 illustrates distinctly different discharge patters depending on parameters of MW radiation and free-stream velocity. In case of multiple discharges, a number of electro-dynamic problems is to be solved to provide stable discharges along the whole z-array of plasma actuators. As a result, the cartridge of ring-type resonant actuators was fabricated for the wind-tunnel measurements. The airfoil model with generated discharges is shown in the right low corner of Figure 4.

Transfer of the discharge-initiation technology to wind-tunnel experiments showed a number of problems which are to be taken into account in specific full-scale experiments. One of them is the generation of a uniform field in the area of initiators. The standing EM wave mode (Figure 5) provides the delivery of energy sufficient to initiate

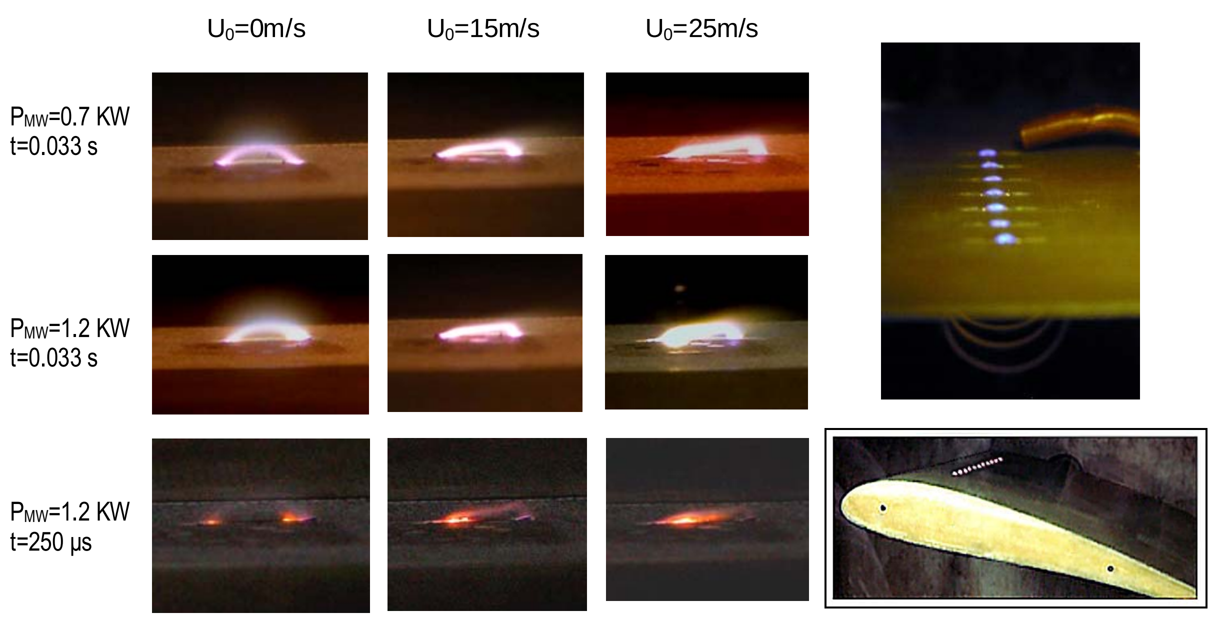


Figure 4. Single MW-initiated plasma discharges in a desktop jet facility and multiple discharges in the jet flow and over a model in the wind-tunnel test section depending on parameters of MW radiation and free-stream velocity, λ_z=10 mm

discharges but spatially, it creates difficulties for the operation in a range of the model angles of attack which shifts initiators from the field node. To provide the system flexibility, such engineering nuances required special solutions of mechanical-electrodynamic adjustments.

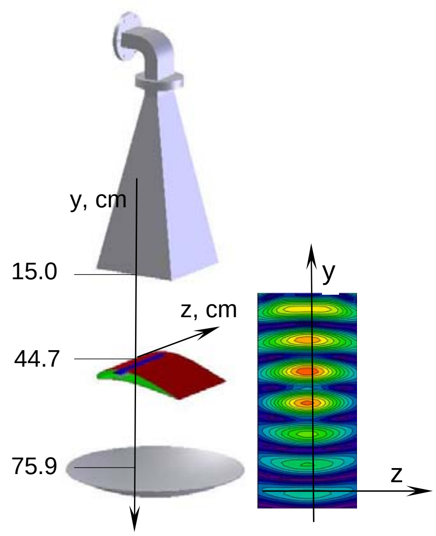


Figure 5. Spatial distribution of electric field in y-z plane in the wind-tunnel test section

MRTI experiments in the jet-flow facility showed that the λ_z=10 mm spanwise scale (a distance between neighboring initiators) could be reached at relatively low levels of energy consumption under the condition of an optimal pulse mode of MW radiation. However initially, it was estimated that the λ_z=5 mm scale was preferable for the given range of basic flow parameters in wind tunnel experiments. Therefore a feasibility to reliably generate smaller vortices was studied in the electro-dynamic part of the research which should cover the whole span of the model. It also displayed a number of engineering problems to be solved transferring the results in the wind tunnel experiments. They are (1) required MW energy/per initiator and (2) uniformity of the EM field along the initiator array. The available hardware did not enable to solve these problems.

It motivated a cycle of numerical simulation of the flow affected with the discharges situated at a larger distance from each other than that initially recommended. The numerical modeling of a boundary-layer flow field in presence of localized thermal sources (Figures 6, 7) showed, firstly, the difference between the vortical structure development in laminar and turbulent environment and, secondly, depending on a distance between thermal sources. It was concluded that the scale of λ_z=10 mm (easier to obtain from the electro-dynamic viewpoint) is still acceptable to expect an adequate response of a boundary layer to imposed disturbances. To get an idea about the flow topology, a 3D compressible flow over a convex cylindrical surface of a constant radius R_0 = 0.8 m was analyzed for U_0 = 20 m/s to match basic flow parameters in wind tunnel experiments. According to MRTI recommendations, the thermal sources of 0.5 x 0.8 mm size with T = 1000°C were placed at 1 mm above the surface; z-spacing was taken as λ_z = 5 and 10 mm, the array was located at a downstream section of x = 4 cm. The downstream development of a vortical system initiated with the thermal sources is displayed in Figures 5, 6 for laminar and turbulent flows as well as for various λ_z values. The double spacing, λ_z = 10 mm, results in a quite different kinematical pattern where initially two vortex pairs were formed between the neighboring sources. It can manifest sub-resonant effects related to the boundary layer receptivity of imposed disturbances. Thus, it was concluded that in case of unavoidable experimental difficulties related to the MW generation of plasma discharges with λ_z = 5 mm, the double distance between forcing thermal sources could be done to maintain almost the same resultant topology of the near-wall flow (Figure 7).

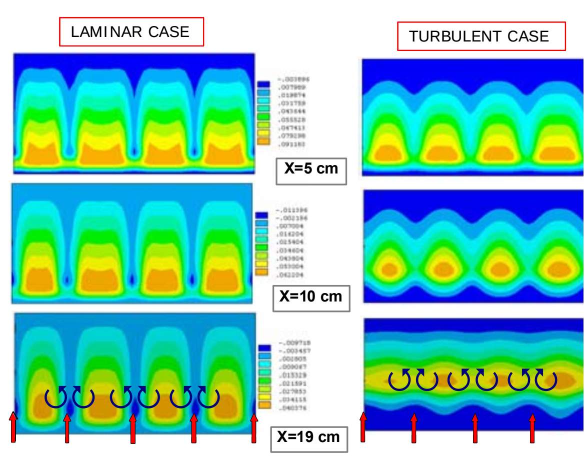


Figure 6. Numerical simulation: Contours of normal velocity over a model without (a) and with (b) imposed temperature sources, λ_z=5 mm

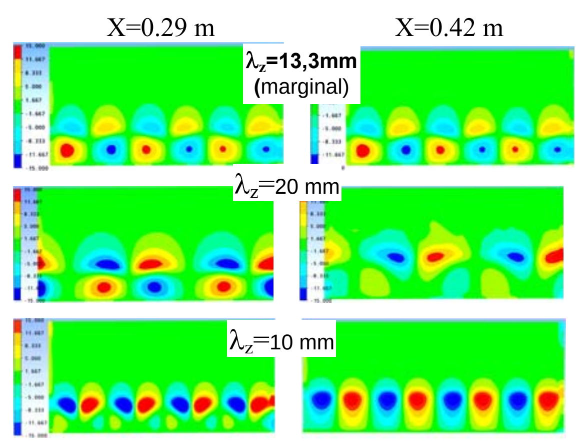


Figure 7. Development of longitudinal vorticity generated in a boundary layer downstream of the spanwise-distributed plasma sources: T~1000°C, U_0=35m/s; ε= 1%

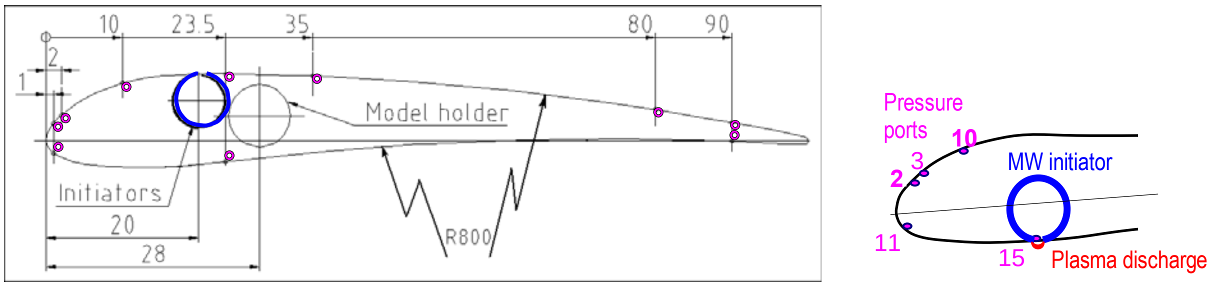


Figure 8. A model with plasma initiators: coordinates of drain ports for pressure measurements

Thus the numerical modeling proved the feasibility of the proposed concept to create given-scale vortical structures in a convex boundary layer by applying localized z-regular high-temperature sources over the model surface. Besides, being matched both with the given electro- and fluid dynamic parameters and experimental possibilities, it gave the practical guidance to design the wind-tunnel experiments.

The airfoil model for aerodynamic experiments with plasma discharges was made of the same geometry and size as the resistively heated model, 20x20 cm, R_{basic}=0.8 m (Figure 8). A generated space scale, a distance between the plasma actuators, was taken as λ_z =10 mm. Free-stream velocities were chosen in a range of U_0=10-20 m/s to enable the comparison of present and earlier results obtained within the same thermal-control strategy but realized through the technique of resistive heating of z-regular temperature sources. Angles-of-attack of most interest are those around a stall area.

The MW system was set to operate in a pulse regime to get sufficient values of radiation energy for stable discharges along the whole spanwise array of 11 actuators which covered a half (an axial part) of the model span. It enabled the usage of a relatively low-power magnetron with MW radiation power of 6 to 8 kW. The pulse duration was 100 µs and pulse frequency f_{MW} = 500 or 1000 Hz. For these conditions, the duty cycle was equal correspondingly to 20 or 10.

Energy estimations with account of a dissipated portion of the radiated energy gave the following: the averaged pulse power of a single thermal source within the plasma array in experiments was 3 to 8 W.

A set of reference tests was carried out without MW-initiated discharges to work out a technique of simultaneous measurements of lift, drag, pitch moment, and pressure coefficients. Pressure was measured in 7 points around the model. All the obtained data were statistically processed both for the reference and controlled cases with the separate results stored to the HD.

The model peculiarities result in a very unstable flow within angles-of attack of 20º - 26º with strong oscillations of lift, drag, pitch moment coefficients and static pressure at drain ports. Therefore their values cannot be precisely determined. But with a number of measurements, average values were found to characterize a general tendency of

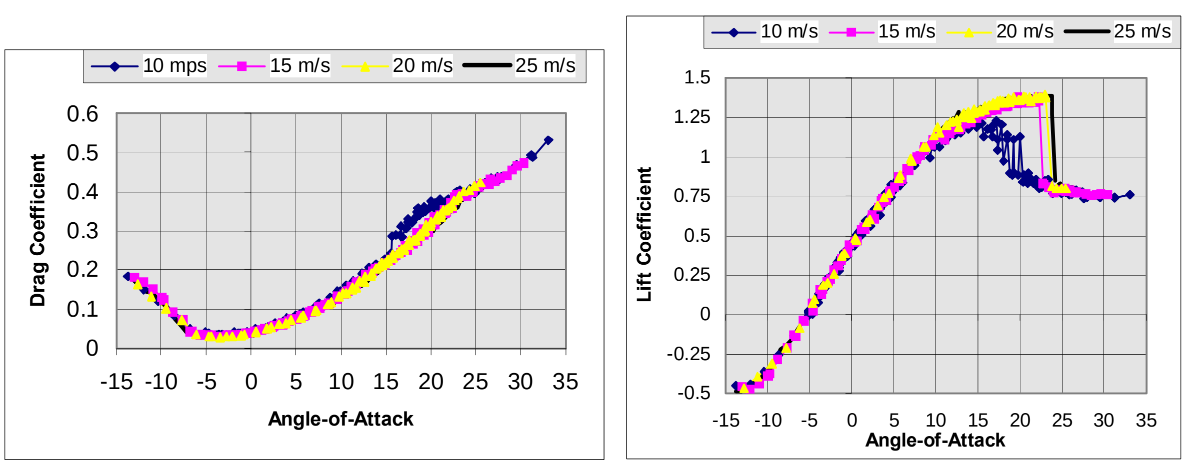


Figure 9. Reference measurements of drag and lift coefficients for various free-stream velocities

the flow to separate and to reattach to the model surface. With that in mind, the following analysis was performed.

Specific flow features around the model are shown in reference measurements of Figure 9 for various values of the free-stream velocity. At 10 m/s, stall begins at a low angle of ~15° and the lift coefficient drop is relatively slow happening within a range of 8°. Drag coefficient grows in this region compared to the higher velocity data. With velocity growing, the stall angle rises up to 22° at 15 m/s. At higher velocities, it slightly increases by ~2° and the lift drop becomes more abrupt. Pitch moment coefficient for a 25% cord position is negative (nose down) beginning from -10° angle of attack and slightly decreases in the region from 0°. This decrease is better seen at 10 m/s in the stall region indicating the stall developing from the trailing edge of the profile that causes a pressure drop on the tail part of a concave surface. In the post-stall region, all curves are again close enough.

Figure 10 shows controlled measurements for the model with only 11 plasma initiators located at 25% of the cord with a spanwise step λ_z=10 mm for combinations of pulse duration and repetition rates at fixed U_0=15 m/s. Plasma discharges in the pre-stall region (angles-of-attack under 24.5º) cause lift coefficients grow by 0.01-0.02 compared to the reference values. Simultaneously, controlled drag coefficients drop by 0.002-0.005. While the stall happens under reference conditions, the flow stays attached under increasing angles of attack within further 0.5º for the controlled model. As a result, the lift coefficient grows by 10-15% at 24.5º-26º angles-of-attack. Correspondingly, the drag coefficient is lower here by 5% compared to the reference case. Similar tendencies are observed in the post-stall region (of 25º-28º angles of attack): lift coefficient is greater by 6-2% and drag coefficient is lower by 6-3% than in a reference case.

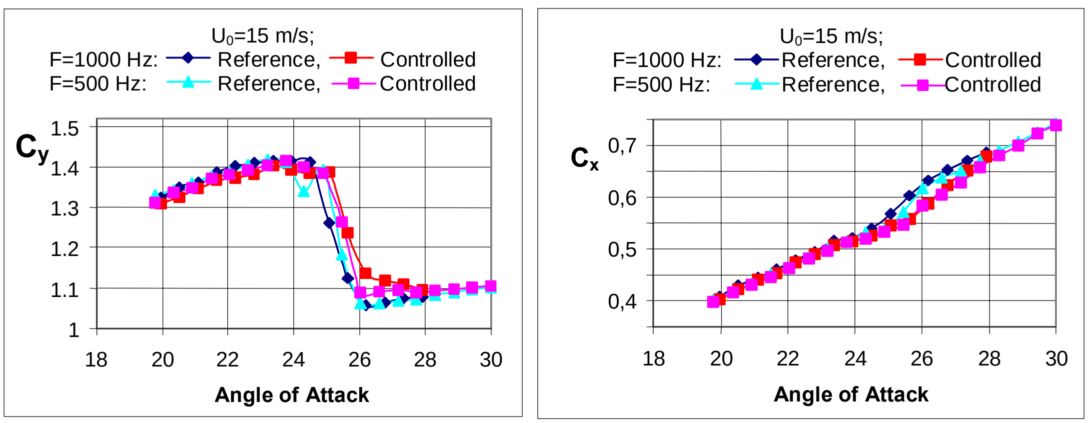


Figure 10. Lift and drag coefficients of the airfoil model at U_0=15 m/s; f_{MW}=1000 and 500 Hz

Measured pressure coefficients in point 1, the very front point of the model, show their change from almost +1 to small negative values and the critical point in the controlled case moves downstream along the convex surface up to α=7° with the angle of attack decreasing. When separation occurs on the concave surface, it shifts the critical point back and, accordingly, changes pressure coefficient to the negative. Pressure ports located downstream on the concave surface show the flow separation and its reattachment in the aft portion of the model up to the angle of attack of at least 9°. The separation bubble

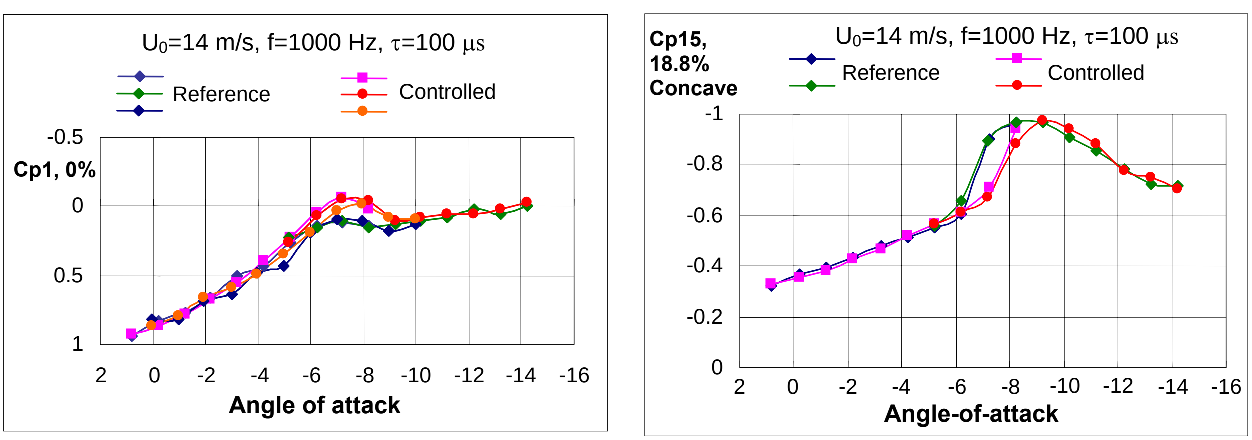


Figure 11. Pressure coefficients of the model at low-to-medium negative angles of attack

chokes the flow in the vicinity of the concave surface thus decreasing the flow rate. This is disadvantageous especially for the blade cascades in compressors that can lead to compressor surging. The applied control postpones this separation by $\alpha \approx 1°$ and even more and thus can broaden a range of stable operation of compressors.

Further measurements were carried out at different free-stream velocities U_0=15, 20 and 30 m/s, large angles of attack and chosen values of the MW pulse duration and repetition rate. High angles of attack were of particular interest because in a linear range of the lift curve discharges caused insignificant changes. Figures 12 show variation of aerodynamic and pressure coefficients in pre- and post-stall regions depending on a geometrical angle of attack of the model. Pressure coefficients are shown for the drain port positions 2% and 10% of the chord (Ports 2 and 10 shown in the Figure). Each point represents a mean value of 5 samples 1.3 s duration so that the total sample duration is 6.5 s for each – reference and controlled case.

Plasma discharges in the pre-stall region reduce lift and drag coefficients that is in accordance with the results obtained for the resistively heated model. Pitch moment coefficients practically do not change. It is confirmed by the pressure measurements at 2% of the cord location: discharges postpone the stall by approximately 0.5°. At 24.5º-26º angles of attack, lift coefficients grow by 0.1-0.15. Accordingly, drag coefficient is lower here by 0.05 than in the reference case. In the post-stall region (25º-28º) lift coefficient is greater by 0.06-0.02 and drag coefficient is lower by 0.006-0.003 in the controlled case. Thus in the post-stall region, lift coefficients remain higher in the controlled case. The negative (nose-down) increment of the pitch moment coefficient displays at least partial flow reattachment in the controlled case. It is in agreement with the C_p graph of Figure 12 where the flow reattachment in an upstream part of the model is seen through the suction recovery.

Certain data scattering is caused by the flow nature in pre- and post-stall regions, i.e. in and between separate 1.3 s samples that leads to deviations of mean values. Besides, insufficient stiffness and circumferential play in the system "model – angle-of-attack drive" led to model position changes under variable loads caused by the flow

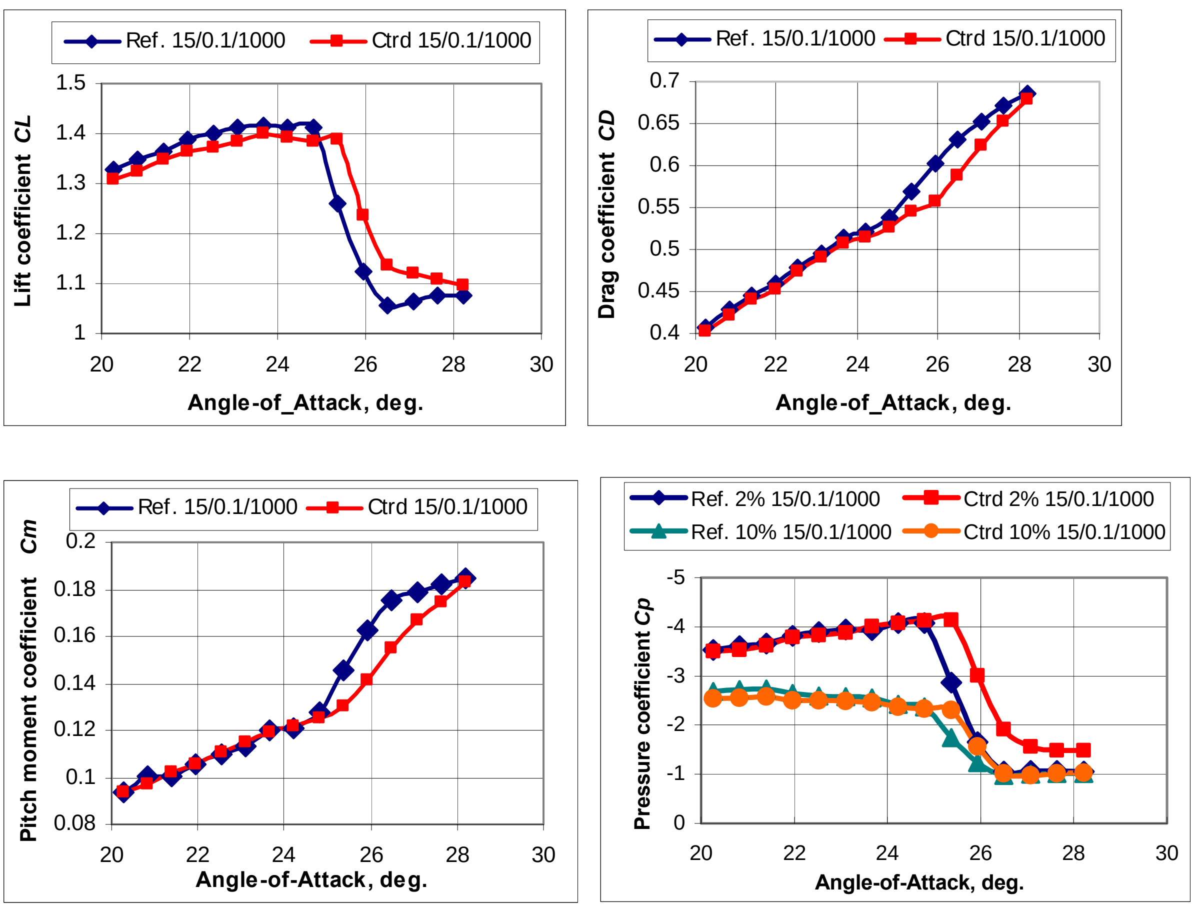


Figure 12. Lift, drag, pitch moment and pressure coefficient for reference (Ref.) and controlled (Ctrd) cases, U_0= 15 m/s, MW pulse regime: f=1000 Hz, t=0.1 s

fluctuations. After the play-removal device was installed on the mechanism, scattering of the data was substantially decreased. Such adjustments are an unavoidable part of wind-tunnel experiments. At low angles-of-attack, random errors were found to be practically independent on free-stream velocities, and standard deviations were as follows: $\sigma_{CL} = 0.004$, $\sigma_{CD} = 0.0008$, and $\sigma_{Cm} = 0.001$ for lift, drag, and pitch moment coefficients respectively. Standard deviations of pressure coefficients were $\sigma_{Cp} = 0.01 \ldots 0.04$.

Greater the released power of MW radiation, greater the flow control effect. It is concluded from the analysis of data obtained for 1000 Hz and 500 Hz pulse repetition rate. Figures 12 show that in the stall and post-stall regions, lift coefficient and pressure coefficient increments for ports 2 & 3 are greater for the greater power, while it affects drag coefficients much less.

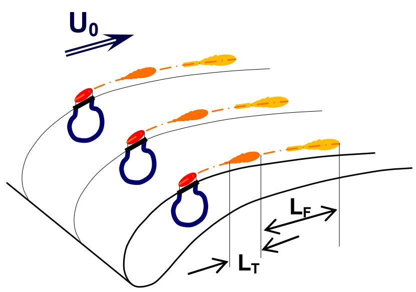


Figure 13. Illustration of a thermal pattern generated in a boundary layer with plasma discharges MW-initiated in a pulse mode

Pulse mode of operation of the plasma initiators was model numerically to reveal the influence of thermal fields intermittency imposed into the boundary-layer flow. Schematically, it is shown in the Figure 13. The task of aerodynamic modeling is to determine the behavior of sequences of heated patches depending on the pulse regime so that the optimal combinations of MW parameters (pulse duration and their repetition rate) could be recommended for the wind tunnel experiments as well as for the electro-dynamic part of the research. Basic flow parameters were taken so that to match the experimental conditions. This matching of all parts of the investigation is one of the most important and valuable features of the discussed multidisciplinary research. For the preliminary aerodynamic estimation, a period of pulse repetition was taken equal to 2 ms (f=500 Hz) with the pulse duration 50 μs (when the thermal sources are on).

Figure 14, left, shows four blue streaks of the temperature T=300°K contours at a moment when the discharges radiated heat during the 50μs

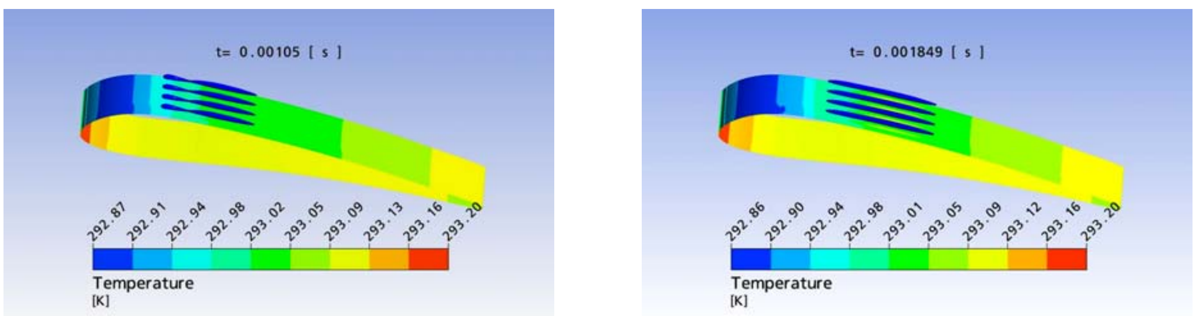


Figure 14. Computed temperature patterns over a model surface for 2 successive MW pulses generating a z-regular array of thermal sources: surface temperature and isosurface of T=300°K; U_0=20 m/s, α=5°, τ=100 μs, repetition rate, f=1000 Hz

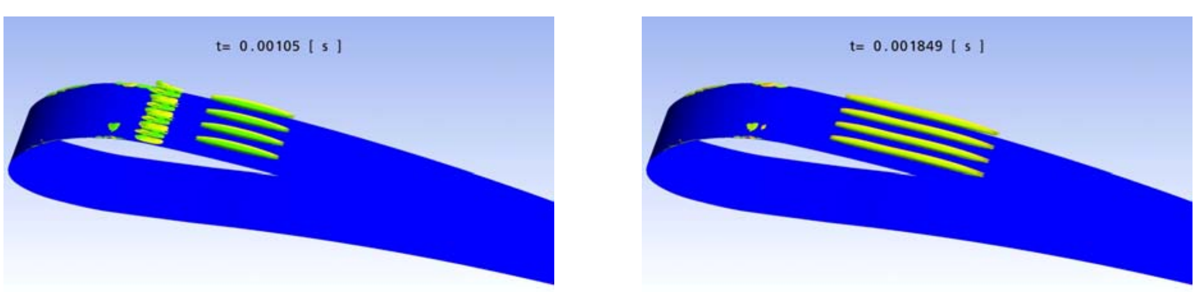


Figure 15. Isosurfaces of streamwise vorticity (±100 s^{-1}); U_0=20 m/s, α=5°, τ=100μs, repetition rate, f=1000 Hz

of a single pulse were switched off. Figure 14, right, shows the downstream propagation and stretching of this heated area during the period of 2 ms until the next radiated MW pulse. The computation results confirm the qualitative assumption of Figure 13 about the thermal field over the model. It is necessary for the physics understanding and as a basis to choose control parameters for experimental investigations. That is within a range of wind-tunnel free-stream velocities of U_0=10-40 m/s, there can be found up to 3-4 sets of z-regular spanwise areas along the model chord at a time.

To see the influence of MW radiation parameters on the thermal patterns over a model and to mimic wind tunnel conditions, similar calculations were done for τ=100 μs and the repetition rate, f=1000 Hz. Figure 14, left, reflects the thermal situation in the flow just after the thermal source was off. Two successive cycles were computed that enabled to see the interaction of successively generated vortical structure at their downstream propagation (Figure 14, right).

Figure 15 shows that the control factor in a form of streamwise z-regular vorticity can be optimized with a proper choice of pulse duration and repetition rate. Propagating downstream within a boundary layer, the two successive portions of streamwise vortices can merge that makes the structural pattern close to the one generated with a constant temperature boundary condition (resistive heating of embedded streamwise elements). It is an encouraging result taking into account the rapidly decaying temperature in the discharge wake: properly chosen pulse parameters enable to enhance the thermal effects due to the downstream merging of the vortices with a given scale.

Thus it was concluded that the available experimental equipment should be sufficient to produce necessary modification of the near-wall flow structure and, accordingly, to obtain expected optimization of lift and drag characteristics of the model.

III. Conclusions

The flow control concept is developed and tested using spanwise-regular MW-initiated plasma discharges. It is based on mild modification of turbulence scales according to the boundary-layer instability feature in a form of streamwise vortices. Numerical and experimental investigation of flows around blade-type models showed a possibility to generate and maintain streamwise vortices of a given scale in laminar and turbulent boundary layers. Their presence was displayed by typical spanwise periodicity of velocity and vorticity distributions.

Drag and lift coefficients are measured for various angles of attack of the model with localized plasma discharges. It is shown experimentally that at U_0= 15 m/s, discharges delay flow separation by 0.5° of an angle-of-attack. This way of the boundary-layer control using localized plasma discharges resulted in lift coefficients growth by 15% together with the 5% decreasing drag. Within the range of tested parameters, greater flow-control effects are obtained for greater averaged MW radiation power.

IV. Acknowledgments

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V. References

[1] Yurchenko, N., “Power of Beauty: streamwise vortices”, *Proceedings of Science & Art Conference*, Kluwer Academic Publishers, Zurich, Switzerland, 2000, pp. 59-64.

[2] Nikiforovich, E., Yurchenko, N., “Boundary-layer flows with centrifugal forces”, *ERCOFTAC Bulletin*, March, 32, 1997, pp. 61-65.

[3] Yurchenko, N., Delfs, J., “Boundary layer control over an active ribleted surface”, *Fluid Mechanics and its Applications*, edited by G.E.A. Meier and P.R. Viswanath, Kluwer Acad. Publishers, Vol.53, 1999, pp. 217-222.

[4] Yurchenko, N., Rivir, R. Pavlovsky, R., Vynogradskyy, P., Zhdanov, A., “Control of the profile aerodynamics using streamwise vortices generated in a boundary layer”, *Proceedings of the World Congress "Aviation in the XXI-st Century",* Kyiv, Ukraine, 2003.

[5] Yurchenko, N., “MW-Generated Plasma Discharges as a Novel Approach to Flow Control”, *Proceedings of 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, U.S.A*., 2008.

[5] Bychkov, V. L., Igor Esakov, I. I., Grachev, L. P., Khodataev K. V., “A microwave discharge initiated by a loop-shaped electromagnetic vibrator on a surface of radio-transparent plate in an airflow, *Proceedings of 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, U.S.A*., 2008.