On a possibility of laminar flow control on a swept wing by means of plasma actuators

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The main reason of laminar-to-turbulent transition in a boundary layer on a swept wing of modern civil airplanes is, as a rule, the cross-flow-type instability. The concept of laminar flow control (LFC) method based on an attenuation of the cross-flow-type instability due to electrogasdynamic (EGD) force impact on three-dimensional boundary layer in the vicinity of a swept wing leading edge was proposed at TsAGI some years ago [1] and is illustrated in Fig. 1. Plasma actuators operating on the base of dielectric barrier discharge (DBD) [2] seem to be very convenient for realization of this method. Volumetric force $\boldsymbol{F}_{\|}$ generated in DBD and directed along a wing leading edge in *z*-direction will induce gas velocity in this direction thereby reduce cross-flow velocity in the boundary layer. In turn, an attenuation of the cross-flow velocity results in a decrease of increments of spatial growth of steady-state modes of the cross-flow-type instability in transonic three-dimensional boundary layer [3].

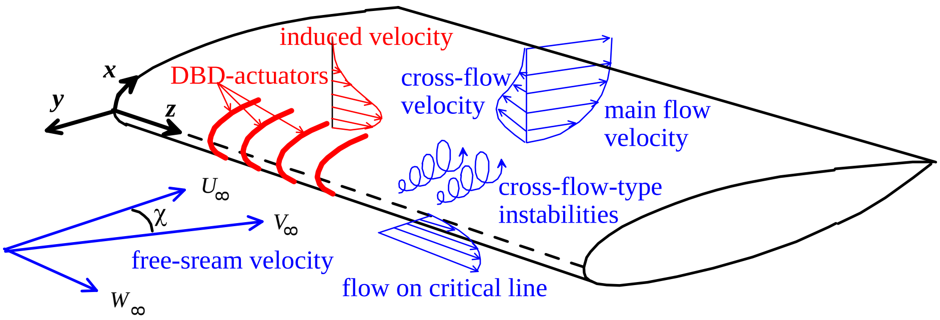

Figure 1. The concept of EGD LFC method on a swept wing.

Optimization of plasma multi-actuator system spatially periodic along a wing leading edge and ensuring force impact along the whole leading edge is a substantial problem for realization of EGD LFC method [4]. The optimal system has to create a volumetric force $\boldsymbol{F}_{\|}$ large enough for prevention the laminar-to-turbulent transition caused by the cross-flow-type instability at moderate electric power consumption. Note, that preliminary theoretical estimations [5] demonstrate possible damaging influence of volumetric heat release in discharge on boundary layer stability when the coefficient of energy efficiency of DBD-actuators is too small.

Experimental study of LFC on a swept wing in wind tunnels for cruise flight conditions is very difficult because of impossibility to reproduce simultaneously transonic Mach number, high Reynolds number, low turbulence level, low static pressure, and necessary geometric parameters. In addition DBD-actuator system consists of a lot of geometrical and physical parameters influencing on its performance characteristics, first of all, volumetric force and heat release. Therefore parametric experimental study of EGD LFC is very labor-consuming. Because of these reasons a preliminary numerical study of this method seems to be relevant.

The main purpose of the present theoretical research consists in the estimation of parameters of the EGD LFC method necessary for significant attenuation of the cross-flow-type instability on a full-size swept wing at transonic cruise flight conditions. The flow over the infinite span swept wing with LV6 airfoil is considered as an example. The force and heat impact of DBD-actuators on compressible boundary layer flow is simulated by volumetric source terms introduced in momentum and energy equations. These terms are given in analytical forms qualitatively reflecting the spatial distributions of the volumetric force and Joule dissipation in DBD obtained on the base of numerical modeling of plasma multi-actuator system [4].

Since the heat impact influences significantly both on the compressible boundary layer flow and on its stability characteristics [5], the equation for average energy of vibrational degrees of freedom of air molecules will be taken into consideration. The case is that a significant part of the discharge power (up to $50 \div 80\%$) is spent initially on vibration excitation of air molecules. Then the vibrational energy transforms into translational degrees of freedom during a finite time thereby influencing on volumetric distribution of gas heating. In the proposed calculations the simplest approximation of the mode kinetics is used. A heating of the exposed electrodes of DBD-actuators due to energy relaxation of incident ions and electrons seems to be the other phenomenon influencing on thermal state of the compressible boundary layer. Therefore special thermal boundary conditions are used in boundary layer calculations to take into consideration this phenomenon.

The spanwise spatial modulation of the boundary layer flow due to non-uniform distributions of volumetric force and heat input may influence on its stability characteristics. Therefore the linear stability of the spatially modulated compressible boundary layer with respect to the steady-state modes of the cross-flow-type instability is studied in the framework of numerical solution of the eigenvalue problem formulated with taking into account the spanwise dependence of the eigenfunctions.

The parametric numerical study of an ability of the EGD LFC method on the base of the described approach is executed.

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