NUMERICAL MODELLING OF CROSS-FLOW DOMINATED TRANSITION CONTROL BY MULTIPLE-ELECTRODES DBD ACTUATORS

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INTRODUCTION

Flow control by means of dielectric barrier discharge (DBD) actuators is studied extensively last ten years. Physics of this type of electric discharge and gas flow induced by it was investigated in [1]. Its action on the gas flow can be modeled by combination of steady body force and heat release [2,3]. Usually DBD actuators were used for airfoil lift enhancement by means of stall prevention [4]. However, such lift control is suitable for low speed only because of weak flow velocity (<10m/sec) induced by DBD. DBD application to boundary layer laminarization seems to be more attractive because of minimal change of velocity profile can improve boundary layer stability. Computations [3] showed that 2-3% increase of near-wall flow velocity leads to two-fold increase of laminar flow region. High efficiency of cross-flow dominated transition control by DBD for transonic speed was demonstrated in theoretical work [5].

NUMERICAL METHOD

Plasma actuators for cross-flow instability control can be conceived as a large number of electrodes distributed over the forward part of the wing surface. Configuration of electrodes of such actuator is shown in Fig. 1.

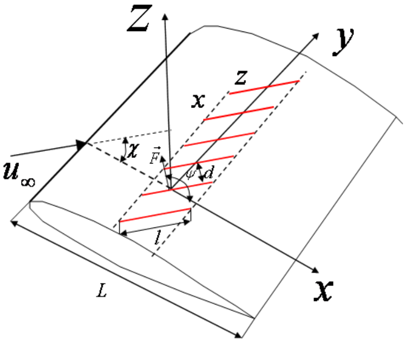

Fig 1. Scheme of multi-electrode DBD actuator

It is assumed that the action of discharge on the flow can be modeled by the body forces $\vec{F}'$ located in the vicinity of the working edges of electrodes. These forces are assumed to be directed parallel to surface and perpendicular to electrodes. Angle between x axis and direction of discharge induced force is denoted as ψ. Air heating by discharge is rather weak, so model of incompressible fluid with constant density and viscosity will be used further. Non-dimensional variables are introduced using boundary layer thickness $\delta' = (\nu L'/u_\infty)^{1/2}$ and free-stream velocity u_∞ as scales.

Solution near the actuator is sought as a sum of basic flow with velocity components $U_0(z)$, $V_0(z)$ and finite amplitude perturbations u,v,w,p induced by discharge. Longitudinal size of actuator is assumed to be small with respect to wing chord, so basic flow is presumed to be uniform along x and y. Discharge-induced disturbances are governed by Navier-Stokes equations

$$
\begin{aligned}
&U_0\frac{\partial u}{\partial x}+\frac{dU_0}{dz}w+V_0\frac{\partial u}{\partial y}+N_x=-\frac{\partial p}{\partial x}+F_x+\frac{1}{R}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)\\
&U_0\frac{\partial v}{\partial x}+V_0\frac{\partial v}{\partial y}+\frac{dV_0}{dz}w+N_y=-\frac{\partial p}{\partial y}+F_y+\frac{1}{R}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)\\
&U_0\frac{\partial w}{\partial x}+V_0\frac{\partial w}{\partial y}+N_z=-\frac{\partial p}{\partial z}+\frac{1}{R}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)\\
&\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0\\
&u,v,w(x,0)=u,v,w(x,\infty)=u,v,w(x,\pm\infty)=0
\end{aligned}
\tag{1}
$$

with non-dimensional force terms

$$F_x=F_x'\delta/(\rho u_\infty^2),\ F_y=F_y'\delta/(\rho u_\infty^2)\cdot \tag{2}$$

In these equations $R=u_\infty\delta'/\nu$ is Reynolds number and N_x, N_y, N_z, - non-linear terms.

For simplicity infinite span wing with periodical set of electrodes is considered. Perturbations are sought in form of combination of Fourier series in y and Fourier integral in x. Application of such 2D Fourier transform to (1) and elimination of pressure reduces it to Orr-Sommerfeld and Squire equations with right parts containing Fourier transforms of body force and non-linear terms. These equations were solved by matrix method based on collocation technique. Non-linear terms were found by iterations.

PHENOMENOLOGICAL MODEL OF DBD-INDUCED FORCE

Expression for horizontal component of body force produced by DBD was derived in order to fit PIV data in [6].

$$F=\theta(\bar{x})\frac{F_\Sigma}{x_0 z_0}\bar{x}\,\bar{z}\,e^{-(\bar{x}+\bar{z})};\ \bar{x}=\frac{x}{x_0};\quad \bar{z}=\frac{z}{z_0}$$

Here F [N/m^3] – body force density, F_Σ [N/m] – integral force produced by discharge, x_0, z_0- coordinates of maximum of body force, $\theta(\bar{x})$ - Heaviside function. In subsequent computations parameters of model $F_\Sigma = 7.1\times10^{-3}$ N/m, x_0=0.67mm, z_0=0.67mm corresponding to discharge with high-voltage amplitude 4.4kV and frequency f=6.25kHz were used.

INFLUENCE OF DISCHARGE ON BOUNDARY LAYER FLOW AND CROSS-FLOW INSTABILITY

Numerical method developed in previous sections was applied to numerical modeling of cross-flow instability control by means of multi-electrode actuator. Computations were performed for conditions of planned experiment which will be performed with model of swept-wing section of chord 1m, sweep angle 35^0 and flow velocity 40m/s. Folkner-Scan-Cook self-similar solution

$$U_{0v} = \left(\frac{x'}{L'}\right)^m f'(\eta)\cos\chi; \quad V_{0v} = g'(\eta)\sin\chi$$

$$\eta = \frac{z\sqrt{m\cos\chi}}{\sqrt{\beta}(x'/L')^{\frac{1-m}{2}}}; \quad \beta = \frac{2m}{m+1}$$

$$f''' + ff'' + \beta(1-f'^2) = 0; \ f(0) = f'(0) = 0; \ f'(\infty) = 1$$

$$g''' + fg'' = 0; \quad g(0) = g'(0) = 0; \quad g'(\infty) = 1$$

with m=0.29 was used as a model of oncoming boundary layer. It well approximates swept-wing boundary layer in the region of strong cross-flow instability. The actuator was placed between x=0.4 and 0.6m and had period of electrodes d=14mm. Boundary layer thickness in the middle of actuator equals to δ=0.6mm and Reynolds number R=1700.

Main purpose of work was finding of optimal angle of electrodes ψ resulting in maximal control efficiency. Influence of this parameter on cross-flow velocity profile above the actuator shows Fig. 2, a. It reveals that actuator with parallel to leading edge electrodes creating velocity directed to it is the most effective from the point of view of cross-flow velocity reduction. However, Fig.2b shows that such actuators retards parallel to external streamline velocity in the boundary layer and initiate the instability to Tollmien-Schlichting waves.

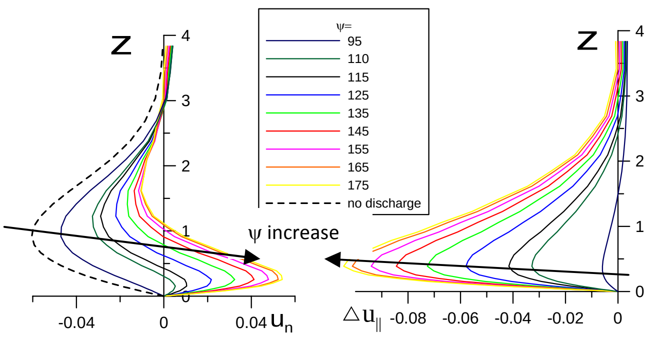

Fig 2. Averaged over the span profiles of cross-flow velocity (a) and increment of tangential velocity (b) in the boundary layer at x=0.55m for different electrode inclination angle ψ

Stability computations based on spanwise-averaged velocity profiles showed that optimal angle of electrodes is close to direction of external streamline. For configuration considered here it is near 115^0. Influence of actuator with this electrodes angle on the boundary layer stability shows Fig. 3. Discharge entirely eliminates instability with respect to steady modes and reduces the maximal growth rate of travelling modes by factor of 3. After the actuator boundary layer rapidly relaxes to its initial state, so discharge effectively eliminates cross-flow instability only within the actuator area.

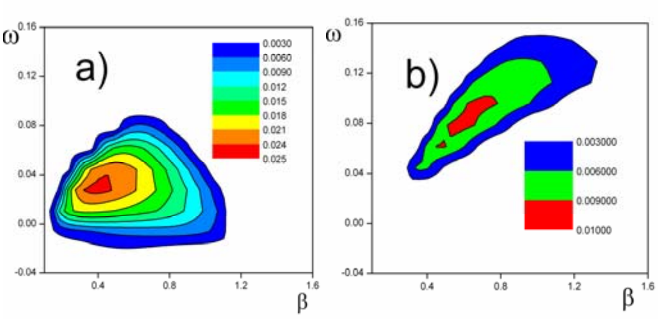

Fig 3. Growth rates of unstable disturbances $\sigma = -\mathrm{Im}(\alpha)$ in oncoming boundary layer (a) and in averaged flow above the actuator with ψ=115^0 at x=0.6m.

Expression for non-dimensional force terms permits us to estimate the parameters of discharge necessary for prevention of cross-flow instability at the wing of passenger aircraft. From (2) it was found that discharge with F=2-5x10^{-2}*N/m* on the actuator with period of electrodes *d=6mm* is enough for prevention of cross-flow dominated transition on the swept-wing in cruiser flight conditions.

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