ACTIVE FLOW CONTROL ON THE SIMPLIFIED FLAPPED AIRFOIL

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OVERVIEW

The paper deals with the control and influence of synthetic jets on the flow field under the conditions close to the boundary layer separation. The boundary layer separation has a considerable effect on efficiency of turbomachines and fundamental effect on aircraft wing sections performance. By the boundary layer control, it is possible to obtain both operational economy and extension of efficient operation region. Modern methods based on the control by synthetic jets are simpler, but their design has to be carried out at rather well experience and detailed knowledge about the boundary layer and its interaction with the actuator.

Two types of synthetic jets were used on two test methods cases on simplified airfoil with flap. First measured task was focused on laminar separation bubble suppression, the other on delay of turbulent separation on the flap. The influence of jet output geometry was studied on a row of orifices and on a slot. Variation of control frequencies was performed.

1. INTRODUCTION

The design of aircraft airfoils is based on the fixed parameters and it is possible to optimize them for given conditions. Because airplane must operate under wide extent of regimes, there are opportunities to use active or passive control of the flow field. Passive methods can be reasonably applied under requirement of minimal negative impact in off-design conditions. On the other hand, it is possible to apply active methods in the most of conditions. Other question is a suitable design of actuators, which should take the reflection to the changing parameters of the flow.

2. FLOW CONTROL MECHANISM

At first we should summarize, which methods can be applied to eliminate negative effects of a flow. Comparing passive and active methods of the shear layers control we can clearly see the basic differences between them. Applications of passive methods add momentum to the shear layer from the main stream by the modifications of the surface geometry only (turbulator, surface roughness, etc.). The active methods require some process or equipment to supply additional momentum to the shear layer. Active methods can also be very easy adapted to the varying conditions of the flow (free stream velocity, turbulence intensity, position of separation point, etc.) contrary to the passive methods.

2.1. Active methods of flow control

Conventional methods of active flow control are steady suction and blowing, but compared to new active methods of flow control as a synthetic jet, oscillating flap or ribbon, an acoustic excitation or a plasma flow control etc., is their efficiency very low. Basic idea of new methods is not only to modify momentum distribution along the thickness of the shear layer, but to add the vortex structures to delay flow separation, as well minimum change of mass flux of the main flow. Alternating suction and blowing can be generated using a synthetic jet. Frequency, intensity, direction and magnitude of output momentum of this jet should be optimized in relation to the dimension of the controlled region, dimension of a shear layer thickness, velocity, etc. Using this also generates vortices structures, which effect alternation to the character of a shear layer. It can be matched to the pulling of heavy stone on the cylinders.

Synthetic jet excitation is more effective and efficient than steady blowing or suction [6, 4]. Great advantage of this method is zero mass flux supplied to, or taken from main flow. By application of this method we can arrange position of transition point from laminar to turbulent boundary layer and in the case of turbulent boundary layer it is possible to delay its separation. Therefore this method is more sophisticated and assumes good knowledge of the physical process description.

2.1.1. Synthetic jet

This flow control actuator is designed as a cavity with periodically moving wall and with orifice or slot, which generates a synthetics jet. (See also [1, 2, and 3]). Fig. 1 depicts direction of the flow round the orifice. There exist two main lines of the flow caused by two phase of the jet operation. Direction of first one is along the central line of the orifice. Second phase, suction, brings air along the wall into the orifice.

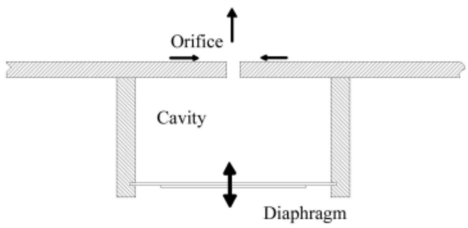

FIG 1. Model of zero net mass flux – synthetic jet

Synthetic jet can be also generated using steady blowing and appropriate acoustic design of cavity and orifice without supplying of energy. That possibility is more suitable for sailplane.

To determine the intensity of synthetic jet, the total momentum coefficient C_μ can be used the definition stands [3, 5]:

$$C_\mu = \frac{\rho_j U_j^2 h}{1/2 \rho_\infty U_\infty^2 c} \tag{1}$$

where U_∞ and ρ_∞ are velocity of the outer flow and fluid density respectively, U_j, ρ_j are the same quantities related to jet fluid, h is the jet orifice diameter or width of slot, c is the typical dimension of the body. Value of the total momentum coefficient is changed from 0.1% to 3% for synthetic jet boundary layer control.

To obtain optimal frequency to the maximum output velocity of the synthetic jet actuator have to be used dimensionless frequency F^+ (2), Reynolds number of the orifice (3) and Stokes number (4) of the orifice. They are defined as:

$$F^+ = \frac{f \cdot X_{te}}{U} \tag{2}$$

$$\mathrm{Re}_0 = \frac{U_0 \cdot h}{\upsilon} \tag{3}$$

$$St = \frac{f \cdot h^2}{\upsilon} \tag{4}$$

were f – actuated frequency, X_{te} – dimension of controlled region (such as distance between actuator and trailing edge), U – free stream velocity, h – width of slot, U_0 – mean velocity from the slot.

From previous works optimum of dimensionless frequency has been determined to fit into interval form one to ten. We should point out that the change of F^+ strongly affects the minimum of the total momentum coefficient, which is capable to control the flow. Values of Re_0 and St are influenced as well.

2.1.2. Synthetic jet actuator design

Design of synthetic jet actuator is based on the Lumped Element Model – LEM theory. To exert LEM theory must be complied basic precondition and that's characteristics length scale of excite frequencies of the actuator must be larger than the largest dimension of the actuator. If the basic term is accomplished, the governing partial differential equations of the dynamic system of the synthetic jet actuator can be easily transferred into a set of coupled ordinary differential equations. Individual parts of actuator components are modelled as elements of an equivalent electrical circuit using conjugate power variables (see Fig.2). The frequency response function of the circuit is derived to obtain an expression for Q_{out}/V_{ac}, the volume flow rate to applied voltage. Idea of the LEM has been introduced in [1,2], where detailed derivation of the model is also shown.

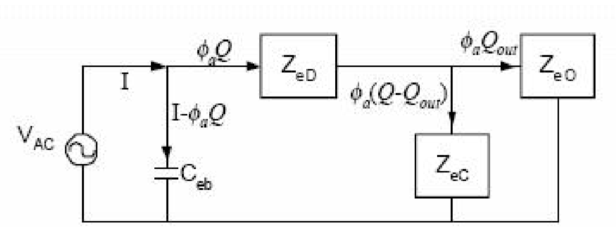

FIG 2. Lumped Element Mode - equivalent electrical circuit (D – diaphragm, O – orifice, C – cavity)

Change of various actuator parameters (width of slot, volume of cavity, property of cavity, etc.) has significant effect to dynamical behaviour of the synthetic jet generator, to the amplitude-frequency response and namely to the velocity amplitude of the air coming out of the orifice.

We can clearly see possibility to optimize the actuator parameters to obtain maximum output velocity or momentum of the flow, wide frequency range with high velocity output etc. [2]. However there are problems to estimate constants, for example material constants as an impact of the wall acoustic rigidity etc. It is necessary to verify them experimentally.

3. MODEL DESIGN AND EXPERIMENTAL SETUP

The boundary layer control by the synthetic jet was experimentally tested on the simplified model of an airfoil with a flap. To achieve flexible layout and easy access to actuators, simple geometry was chosen. The position of the actuators and base dimension of the model are depicted on the FIG 5. The angle of flap γ was varied from 22° to 26°. In the first test case, piezo-actuator was used as generator of synthetic jet. It was placed perpendicular to the surface in the region of leading edge (position 1). LEM method was applied for the design of actuator with rectangular slot as a jet output. Calculated and measured amplitude-frequency characteristic are shown on the FIG 6. Excite amplitude was ± 15 V and maximum of the synthetic jet mean velocity in distance of 0.5 mm above the corresponding slot is 25 m/s and frequency of 2600 and 3800 Hz. Width of slot was 0.5 mm.

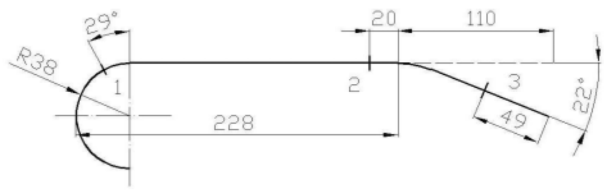

FIG 3. The design of measured model

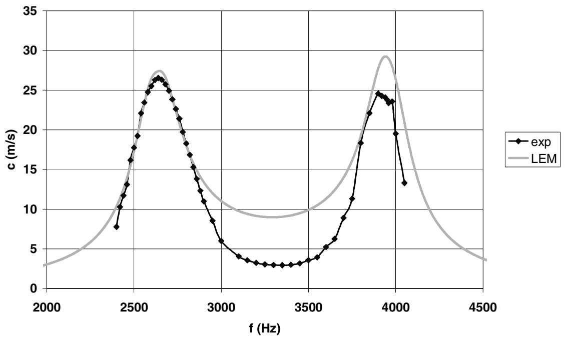

FIG 4. Amplitude-frequency characteristic of piezo-actuator, LEM calculated data and CTA measurement

The second case represents the same model, but controlled by two electrodynamics actuators at position 2 and 3. Synthetic jet actuators were based on speakers of 52 mm diameter as exciters. To get 3D flow field the output was modelled as row of five orifices. The distances between the orifices were 4 mm. Amplitude-frequency characteristic of the actuator was obtained experimentally using hot-wire anemometry. Excite amplitude was ± 2 V and corresponding amplitude-frequency characteristic of the actuator is plotted in FIG 7. Maximum of the synthetic jet mean velocity 1mm above orifice is 11 m/s at frequency of 300 Hz.

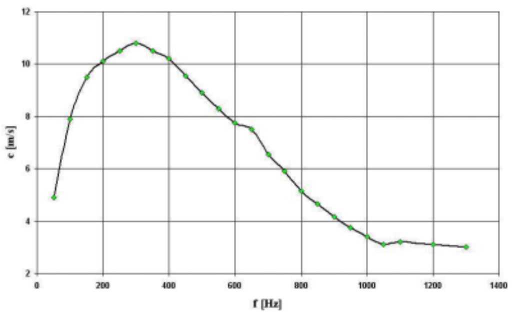

FIG 5. Amplitude-frequency characteristic of the electrodynamic actuator

As the last case, on the same model at position 2 was placed actuator with slot as an output with dimension: length 40 mm and width 0.2 mm. Amplitude-frequency characteristic is depicted on the FIG 8. Maximum of the synthetic jet mean velocity 1 mm above the corresponding slot is 9 m/s at frequency 100 Hz.

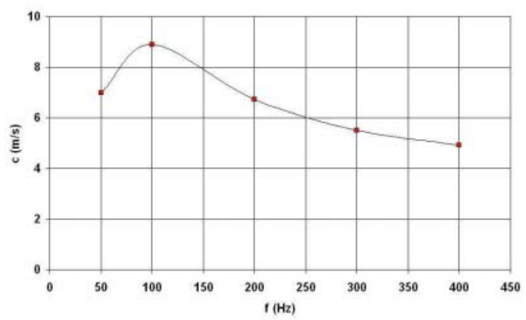

FIG 6. Amplitude-frequency characteristic of the actuator with slot

4. RESULTS

Measurement was carried out by the smoke visualization and PIV method. To compare the differences flow fields of control and no control boundary layer are shown.

Experimental results of the first test case of active control of transition from the laminar to the turbulent boundary layer position are presented on FIG 9. On the upper figure is show up no controlled flow field. The separation bubble can be clearly seen. On the lower side figure is shown flow field controlled by the piezoceramic actuator (synthetic jet). The actuator generates vortex structures, which accelerate the transition from the laminar to the turbulent boundary layer. Thanks to this, the separation bubble can be reduced.

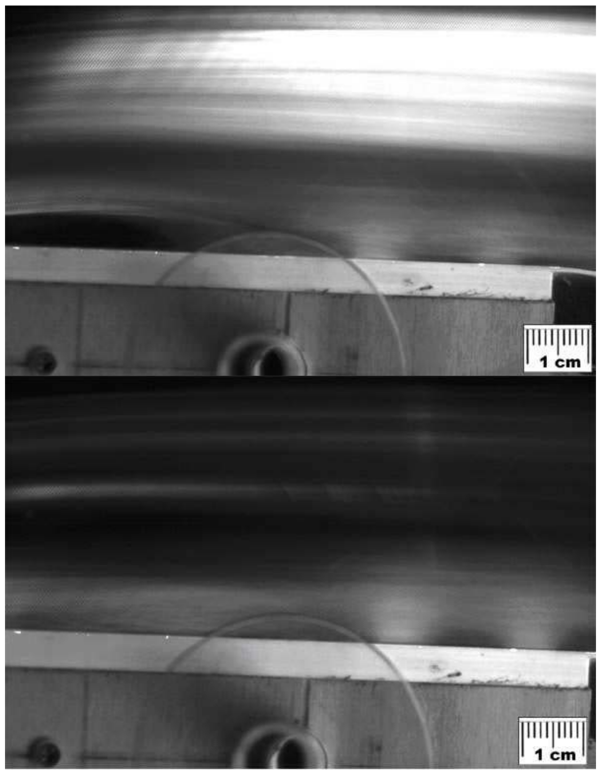

FIG 7. Active control visualization, left figure – no actuated, right figure – actuated, Re = 100 000, Tu = 1 %

The next experiments were focused on the influence of the synthetic jet to the turbulent boundary layer. At first case two synthetic jet actuators at position 2 and 3 were used to control boundary layer. On the FIG 10 are the positions of velocity profiles cuts. On the FIG 11 to 14 are depicted changes of the boundary layer velocity profiles with respect to the free stream velocity, influence of the synthetic jet and cut position on the model.

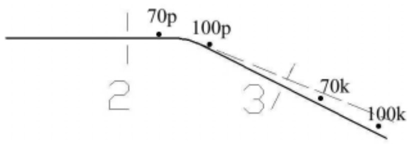

FIG 8 Boundary layer velocity profiles cuts position on the model

On the Fig. 15 fields of vorticity for the angle of flap $\gamma = 22°$ at free stream velocity 3.7 m/s is depicted. There is clear change of intensity vorticity field, which is caused through the influence of the synthetic jet. It is discernible that the synthetic jet on the third position has negative effect to the flow field on the flap. In case of using only the synthetic jet on the second position there would be shown more considerable effect to the flow field on the flap. The intensity of the synthetic jets were not strong enough to differentiate clearly change of the position of the turbulent boundary layer separation.

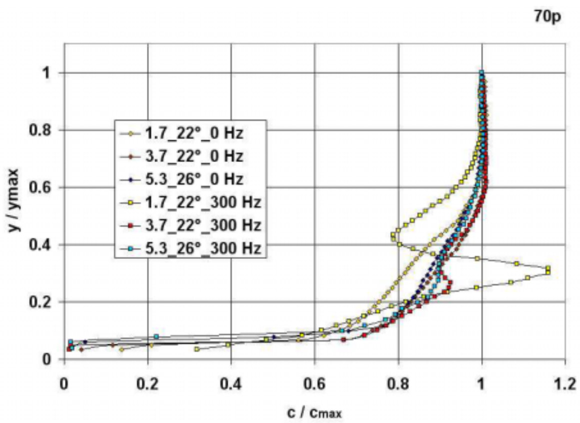

FIG 9 Velocity profiles on the position 70p for the different free stream velocity and influence of the synthetic jet

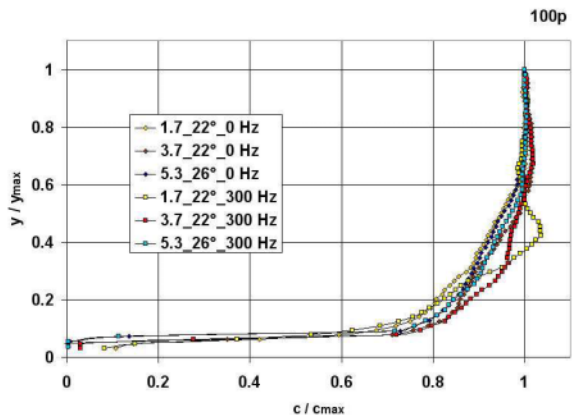

FIG 10 Velocity profiles on the position 100p for the different free stream velocity and influence of the synthetic jet

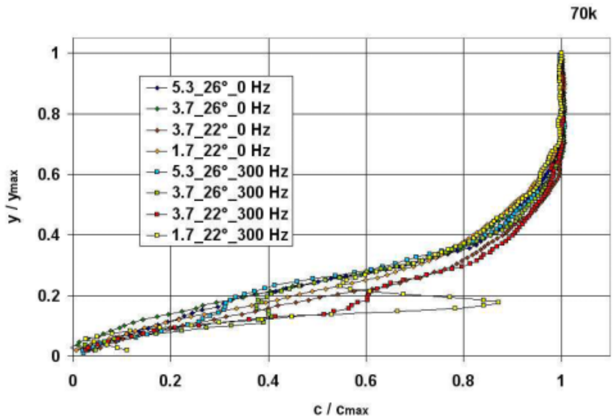

FIG 11 Velocity profiles on the position 70k for the different free stream velocity and influence of the synthetic jet

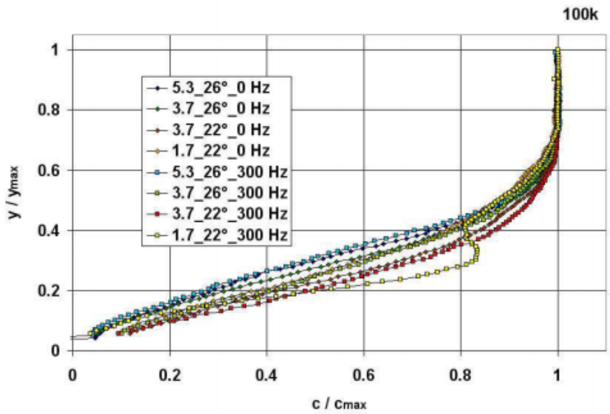

FIG 12 Velocity profiles on the position 100k for the different free stream velocity and influence of the synthetic jet

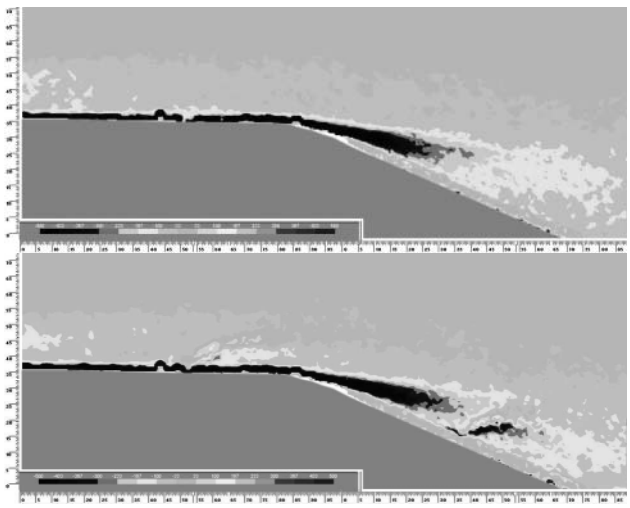

FIG 13 Vorticity fields, Re=80000, c = 3.7 m/s, angle of flap γ=22°, lower figure shows flow field with the synthe tic jets

The synthetic jet actuator with slot at position two was used to control the character of the boundary layer. Angle of the flap on the simplified model was set up to the position $\gamma = 22°$ and free stream velocity 3.9 m/s. Actuated frequency of the synthetic jet was set up on 300 Hz with output velocity 5.5 m/s (total momentum coefficient $C_\mu = 0{,}0024$, dimensionless frequency $F^+ = 10$). On the FIG 16 is position of the velocity profiles from the FIG 17. On the FIG 17 are shown changes of the boundary layer velocity profiles with respect to the influence of synthetic jet. The intensity of the synthetic jet with respect to dimensionless frequency was not strong enough to delay separation on the flap, because the position of slot. Effect of the synthetic jet to the boundary layer is visible till the position 102.

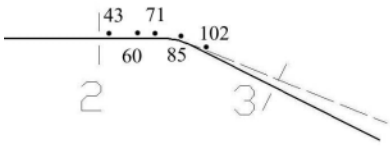

FIG 14 The boundary layer velocity profiles cut position on the simplified model

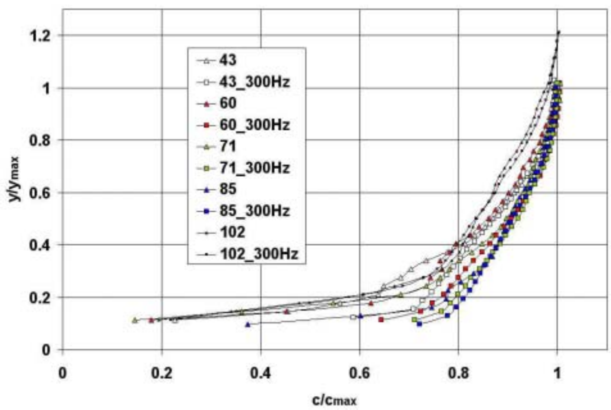

FIG 15 Comparing of the boundary layer velocity profiles on the different positions of cut for free stream velocity 3.9 m/s.

5. CONCLUSION

The potential of active method of control is more extensive, but also more complicated to design. In case of the synthetic jet, there are suitable choices of its designing parameters as F^+, C_μ, etc. In our first case were F^+=145, C_μ=0.11, Re_0=560 and St=40, some of these parameters were out of their ideal range, but an effect to the boundary layer was obtained. The reason is very high value of C_μ (lower efficiency comparing to the ideal case). Decrease value of F^+ and C_μ for higher efficiency of the boundary layer control is necessary.

The second case of application of synthetic jet actuator with row of five orifices was designed with these parameters: F^+=17 - 42, C_μ=0.002 – 0.009, Re_0=340 and St=4.7 (for one orifice). And the last case, the synthetic jet actuator with slot (F^+=10, C_μ=0.0024, Re_0=73 and St=0.8) was tested. In both cases there are considerable impacts of the synthetic jet to the thickness of boundary layer. The direction and the intensity of the synthetic jet on the case two have noticeable impact to the boundary layer. In many cases has indispensable influence an actuator position too, chiefly with respect to the position of boundary layer separation. The synthetic jet actuator with slot is more efficient than the actuator with line of orifices.

6. ACKNOWLEDGMENT

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