MAIN FACTORS OF APPLICATION OF ACTIVE METHODS OF THE BOUNDARY LAYER CONTROL TO THE COMPRESSOR BLADE CASCADE FLOW

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ABSTRACT

The main emphasis of the paper is turned on application of the active methods of flow control, namely of the synthetic jet and plasma flow control into the compressor blade cascade flow. Positive effect of active methods of flow control on the value of losses and main flow vortex structures are discussed.

INTRODUCTION

Energy transformation dissipative processes in the engines have not yet been fully explored. Particularly, it is necessary to get more insight into the issue of energy dependencies in the flow under influence of new active methods of flow control, e.g. by synthetic jet.

The existing experience with active methods of flow control point to the possibilities of effect of local and global structure of the flow field (e.g. acceleration of transition from laminar to turbulent boundary layer, vector controlled of fluid stream, increase of intensity of mass transportation, etc.). It is possible to create a boundary layer more resistant to the adverse pressure gradient without origin of separation bubble or boundary layer separation by the application of synthetic jet, plasma control, etc. Transport of mass and energy between the main stream and outer part of the flow field can also be increased using synthetic jet.

SYNTHETIC JET ACTUATOR

The principle of synthetic jet is based on alternating suction and blowing, which produce a formation of vortices, [1], [2]. Maximum effect is achieved when output orifice is a rectangular - slot, which generates cylindrical transverse vortices. Cylindrical transverse vortex intensity depends on exciting frequency of synthetic jet. Due to this fact reduction or growth of the shear layer (boundary layer) appears. The direction, frequency and magnitude of output momentum of the synthetic jet should be optimized in relation to the thickness of the shear layer, velocity, dimension of the controlled region, etc.

Factors affecting the design of a synthetic jet actuator

Fundamental factors for the design of a synthetic jet actuator are nondimensional frequency (Strouhal number) F^+, Stokes number St of the outlet orifice, Reynolds number of the outlet orifice Re_o and unsteady component of the momentum coefficient c_μ, [1].

$$F^+ = \frac{f \cdot X_{te}}{U_\infty} \tag{1}$$

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

$$\mathrm{Re}_o = \frac{\overline{u}_o \cdot d_h}{\nu} \tag{3}$$

$$c_\mu = \frac{\rho_o \cdot \int_0^h \overline{u}_o^{\,2}(y)dy}{1/2\rho_\infty U_\infty^2 c} \doteq \frac{\rho_o u_o'^2 h}{1/2\rho_\infty U_\infty^2 c} \tag{4}$$

where f is exciting frequency, X_{te} is characteristic dimension (dimension of controlled region), U_∞ is main flow velocity, h is characteristic dimension of the output orifice, ν is kinematic viscosity, c is characteristic dimension of the model, u_o' is mean velocity in output orifice of the synthetic jet generator, d_h is hydraulic diameter, and ρ_o and ρ_∞ are the density inside the output orifice and main flow density respectively.

The design of the synthetic jet actuator is based on the optimal value of variables mentioned above. The optimal value of Strouhal number F^+ for delayed turbulent boundary layer separation is about 1.2. From the optimal value of Strouhal number, main flow velocity and dimension controlled by the synthetic jet can be calculated exciting frequency. Optimal value of the Stokes number St is approx. 1, which indicates a nearly laminar velocity profile in the outlet of synthetic jet actuator. From optimal value of Stokes number it is possible to obtain size of output orifice h. Now can be calculated Reynolds number of the orifice, which must be higher when its critical value $Re_{crit} = 50$. Unsteady part of momentum coefficient c_μ defines the intensity of synthetic jet. The lowest value of c_μ, which has still an inconsiderable impact to the boundary layer, can be obtained for optimal parameters mentioned above. Obvious minimal value of cm is about 0.0004. For a non-optimal value of nondimensional frequency F^+ and Stokes number St, the intensity of the unsteady part of momentum coefficient c_μ must be noticeably higher to achieve the same effect on the boundary layer. The efficiency of the boundary layer control is therefore closely connected to the value of momentum coefficient c_μ. A synthetic jet actuator can be designed on the basis of Lumped Element Theory [3].

PLASMA FLOW CONTROL

The principle of plasma flow control is based on alternating ionization of gas, which accelerate velocity near the surface of the body, [4]. Maximum effect is achieved when voltage above 6kV is applied. Exciting frequency and distance of electrode depends on character of boundary layer and design of the plasma control has to take it in account. The physical principle has been described in ref. [4]. During the first half-cycle, the upper negative electrode is emitting electrons which ionize the neutral air molecules on their way to the lower electrode of opposite charge. The electrons gather on the insulation film of the lower electrode, while the predominantly positive ions are accelerated towards the negative upper electrode. They transfer their momentum to the air and cause a body force affecting the air. Direction of the body force is opposite to the observed wall jet. After the change of the polarity of the driving voltage (second half-cycle), the number of electrons is one order higher than at the beginning of the first half-cycle. Therefore, when the ions move towards the lower electrode, due to their larger number they cause a higher body force than that in the first half-cycle. Now the force is in the same direction as the observed flow.

POSITION OF SYNTHETIC JET ACTUATOR, PLASMA CONTROL WITH RESPECT TO THE CHARACTER OF THE BOUNDARY LAYER

The influence of the synthetic jet depends not only on appropriate design of synthetic jet actuator, but also on position and direction of output slot of synthetic jet actuator. The output slot of the synthetic jet actuator can be placed on the surfaces of blades or the side wall of the tunnel. The output slot of synthetic jet at position in side wall of the tunnel has a fundamental effect mainly on the value of secondary losses, magnitude and intensity of vortex structures. In case its position on the surface of the blade (output slot in position between leading edge and maximum thickness of the blade) has significant impact on both the profile losses and secondary losses.

More sophisticated methods of flow control in the compressor blade cascade are to apply the synthetic jets actuator in both positions on the surface of blades and the side walls or plasma control on the surface of blades and synthetic jet actuator on the side walls. But there is the question of vortices interaction, because interaction of two vortices with their perpendicular axes has not yet been studied. It is possible to assume that the different exciting frequency of the synthetic jets (plasma flow control) will have obvious effect.

RESULTS AND DISCUSSION

From the visualization on the side wall of the tunnel, Figures 1 and 2, positive influence of the synthetic jet to flow field can be clearly seen, [5], [6]. In Figures 1 and 2 change of deviation of the flow and wake development on the side wall is shown and highlighted in red color. From the point of view of wake extend, the higher exciting frequency is much better. Green color highlights development of secondary flow near the side wall. The angle between the pressure side of blade (lower part, Fig. 1 and 2) and green line is dependent on exciting frequency. Value of the angle is lowest for the exciting frequency f_1. There are changes of green line deflection which depend on the exciting frequency, too.

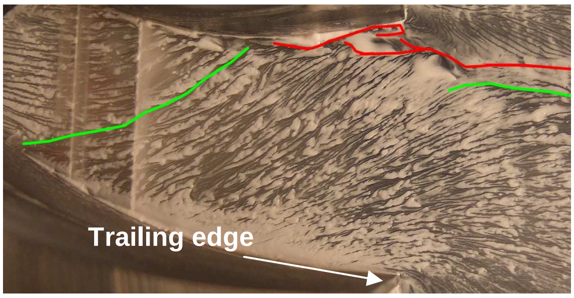

Fig. 1: Visualization of the side wall of the tunnel, no excitation, f_0

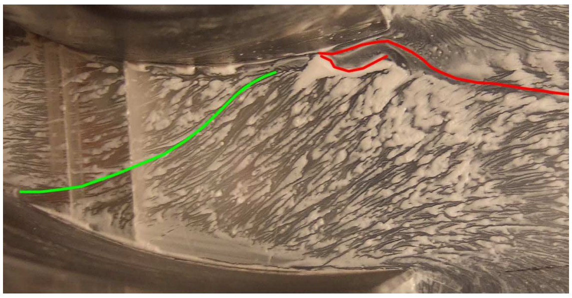

Fig. 2: Visualization of the side wall of the tunnel, output slot of synthetic jet actuator on the side wall, excitation frequency f_3

There are many very important aerodynamics parameters as flow deviation, loss coefficient, AVDR etc., which can describe influence of synthetic jet to the flow field into the compressor blade cascade. However, prime information is the energy efficiency of synthetic jet. The efficiency of the synthetic jet η_{sj}, eq. (8) is defined by the difference of the added work and the specific saved up work to the added work. Specific saved up work w_s can be formulated from the difference of the total loss coefficients with and without the influence of the synthetic jet, eq. (6). The specific work loss w_{loss} can be calculated from the total loss coefficient and the input value of the main flow velocity, eq. (5). From the relation of input electric power P to the mass flow $\dot{m}$ in the controlled region (e.g. blade channel) we can obtain the specific added work, eq. (7).

An evaluation of the influence of the synthetic jet on the flow field from point of view of energy transformations plays a crucial role in flow control.

$$w_{loss} = \overline{\zeta}_T \cdot \frac{1}{2} \cdot U_\infty^2 \tag{5}$$

$$w_s = \left[\overline{\zeta}_T(0) - \overline{\zeta}_T(f)\right] \cdot \frac{1}{2} \cdot U_\infty^2 \tag{6}$$

$$w_{add} = \frac{P}{\dot{m}} \tag{7}$$

$$\eta_{sj} = \frac{w_{add} - w_s}{w_{add}} \tag{8}$$

The efficiency of the synthetic jet expresses how many energy is saved in relation to the added energy. For example in Tab. 1 is shown the ranges of efficiency of the synthetic jet for tree excitation frequencies from f_0 to f_3 and output slot width h. The maximum efficiency of the synthetic jet η_{sj} = -0.84 for excitation frequency f_3 and width of synthetic jet actuator output slot h. In this case, almost 2 times more saved up energy was obtained in relation to the added energy.

η_{sj}				
h	f_0	f_1	f_2	f_3
0.2	1	0.28	-0.44	-0.84
0.5	1	2.74	1.51	0.63
1	1	2.48	0.66	0.57

Tab. 1 Efficiency of the synthetic jet

CONCLUSION

Design of the synthetic jet generator is based on the characteristic dimension X_{te} (dimension of controlled region by synthetic jet). Due to the influence of synthetic jet not only to the boundary layer, but also to the vortex structure, as it was mentioned above, is in specific case determination of characteristic dimension X_{te} questionable. Application of two synthetic jets (plasma control array) placed both on the blade and side wall to affect flow field in the blade cascade and to reduce loss, needs good knowledge on their interaction. It can be assumed that the different exciting frequency of the synthetic jets will also have a significant effect.

Crucial roll in turbomachines plays efficiency. From that point of view is important to know how many times energy was saved in the case of application of active method of flow control comparing to the added energy. Therefore, the efficiency of the synthetic jet η_{sj} was defined. It is good to mention that not only reduction of loss coefficient on one stage of turbomachine is conductive to raise efficiency, but is also useful to control (change) structures into flow field, which has an appreciable impact to next stages.

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