AN EXPERIMENTAL STUDY ON THE EFFECT OF AMPLITUDE MODULATION OF THE SYNTHETIC JET FLOW ON THE CONTROL OF THE WAKE

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Abstract

The paper deals with an experimental research of an active boundary layer control achieved by using periodic excitation of a synthetic jet. The main emphasis of the paper is placed on an influence of amplitude modulation of the synthetic jet flow control. It summarizes the influence of the basic factors that affect the design of the synthetic jet actuator, particularly Strouhal number – nondimensional frequency (F^+), Stokes number of output orifice (St_o), Reynolds number (Re), momentum coefficient (c_μ). The principle of a flow control with and without amplitude modulation was used in order to generate a lower actuating frequency. An amount of input energy of the actuators that influences the flow filed was measured.

1 Introduction

One of the ways to influence the location of the transition from the laminar boundary layer to turbulent one or separation of the boundary layer is to use passive or active methods of a flow control. Passive flow control devices such as vortex generators or boundary layer strips are quite effective to accelerate the transition of the boundary layer from laminar to turbulent, [1]. Delaying the turbulent boundary layer separation can be done by using riblets. Nevertheless, all of these passive techniques are beneficial just for a limited range of operational conditions.

On the other hand, active methods of flow control such as external and internal acoustics excitation, vibrating flaps (ribbons), steady and unsteady suction and blowing and plasma flow control, allow to control the input, induce the flow instabilities and therefore can operate under a wide range of conditions. However, the active flow control methods are based on sophisticated and complicated supporting systems, which need their own power supply devices. Very sophisticated concept is Micro Electronic Mechanical System (MEMS), Glezer & Amitay [2]. The idea of MEMS is based on an interconnection of sensors, actuators and controlling electronics. Several MEMS used synthetic jets for flow control.

Synthetic jets are zero net mass flux active control devices. They consist of an oscillating membrane, a cavity and an output orifice, [3]. Many researchers in experimental and numerical research engaged in using synthetic jets. In the case of airfoils, experimental results have been obtained by Wygnansky [4], Seifert [5], Greenblatt [6] and many others.

The main emphasis of our work is placed on an influence of amplitude modulation of the synthetic jet flow control. The principle of a flow control with amplitude modulation was used in order to generate a lower actuating frequency. An amount of input energy of the actuators that influences the flow filed was measured. Some parts of our work were presented at [7], [8].

2 Model and experimental set up

2.1 Synthetic jet actuators

The design of the synthetic jet generator is based on the requirement to obtain maximum intensity of the synthetic jet with minimum input energy. Therefore, the exciting frequency of the synthetic jet generator should correspond to its resonant frequency. Nevertheless, the efficiency of the flow control depends not only on the intensity of the synthetic jet, but particularly on a value of Strouhal number (nondimensional frequency) F^+.

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

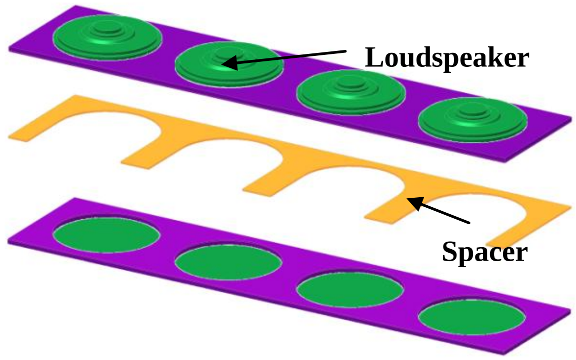

Fig. 1 The synthetic jet actuator

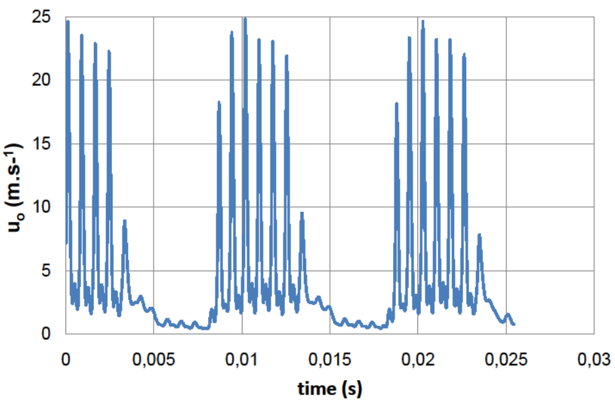

Fig. 2 Magnitude of instantaneous slot output velocity u_o, exciting frequency f_c = 1290 Hz and f_{AM} = 100 Hz, Actuator 1.

Two actuators of synthetic jets in different position were used in this case. Actuators were designed with respect to have a possibility to change their resonant frequencies. Two loudspeakers arranged by two in one cavity were used. Under such an arrangement, the span of the output orifice of one cavity was 25 mm. This configuration enables changes of the volume of the cavity and changes of the width h of slot; the changes are achieved by using various dimension of the spacer. In this case, the width was set up to h = 0.35 mm (Actuator 1) and 0.25 mm (Actuator 2). Schema of the design of the synthetic jet actuator is shown in Figure 1. The length (span) of all the output orifices, 7 slots, in one line is 200 mm – Actuator 1 and 9 slots, in one line 250 mm – Actuator 2. The amplitude frequency response was measured with respect to the input power by using hot wire anemometry (Mini CTA – Dantec) about 0.2 mm above output slot, see Fig. 2, Table 1 and Table 2.

f_c	f_{AM}	$\bar{u}_o$ (m/s)	c_μ %	St
1295	300	9.72	0.0466	10.58
1290	300	9.4	0.0451	10.54
1290	100	11.54	0.0553	10.54

Table 1 Dependence of output velocity $\bar{u}_o$ [m.s^{-1}] on the exciting carrying frequency f_c and modulating frequency f_{AM} [Hz], power input for all slots P = 1.12 W, Actuator 1

f_c	f_{AM}	$\bar{u}_o$ (m/s)	c_μ %	St
1298	200	6.67	0,0228	5.41
1298	250	5.6	0,0192	5.41
1295	300	5.26	0,0180	5.40

Table 2 Dependence of output velocity $\bar{u}_o$ [m.s^{-1}] on the exciting carrying frequency f_c and modulating frequency f_{AM} [Hz], power input for all slots P = 1.44 W, Actuator 2

The synthetic jet actuators were excited by using amplitude frequency modulation. Carrying frequencies f_c = 1290 (Actuator 1) and 1298 Hz (Actuator 2) is the resonant frequency of the actuators. The value of the modulation frequency f_{AM} was chosen with respect to the Strouhal number F$^+$. The sine type waveform of carrying signal was used. The amplitude modulation signal was of a square type with 50% of duty cycle. Dependence of the output velocity u_o on the exciting modulating frequency f_{AM} and on the actuators are shown in Tab 1 and Tab 2. Figure 2 clearly shows the magnitude of instantaneous velocity u_o in the output slot of actuator 1 without the external flow, considering the time, for the exciting modulating frequency f_{AM} = 100 Hz. Value of Stokes number of output orifice St_o (2) and oscillatory momentum coefficient c_μ (3), (4), (5) which is a ratio of the momentum added in the free stream are in Table 1 and 2.

$$St_o = \frac{f \cdot h^2}{\nu} \quad (2)$$

$$c_\mu = \frac{\rho_o \cdot u_o'^2 \cdot h}{1/2 \cdot \rho_\infty \cdot U_\infty^2 \cdot D} \quad (3)$$

where

$$u_o' = \frac{\sqrt{\int_0^h \bar{u}_o(y)^2 dy}}{h} \quad (4)$$

and

$$\bar{u}_o = \frac{1}{T_{AM}} \cdot \int_0^{T_{AM}} \left(\frac{2}{T_C} \cdot \int_0^{\frac{T_C}{2}} u_o(t) \cdot dt_C \right) \cdot dt_{AM} \quad (5)$$

2.2 Model

The model is shown on Fig. 2. It is airfoil NACA 63A418(21) with flap and two actuators of synthetic jets. Position of output slots of actuators is marked on Figure 3 and 4. First actuator is in position upstream starting point of separation bubble aiming to reduce its size. Second actuator is placed in position downstream turbulent reattachment to influence position of separation on the flap. Data acquisition was carried out in wind tunnel of Department of Fluid Dynamics Laboratory of IT, AS CR. The closed circuit wind tunnel has closed test section with dimensions of 865 mm x 485 mm x 900 mm, [11]. The incoming mean flow velocity was fixed at U = 14.5 m/s, Reynolds number Re = 250000 and turbulence intensity about 0.25%. Angle of attack of the model was set up at value α = 0° and angle of flap was set up at 20°. Actuating frequencies were used with respect to optimal value of Strouhal number (nondimenzional frequency) F^+.

Data were obtained using pressure measurement. From pressures measurements were calculated lift coefficient c_L and drag coefficient c_D to compare effect of modulating frequency f_{AM} and intensity of synthetic jets. Lift coefficient c_L was calculated from pressure taps on side wall of the tunnel and drag coefficient was calculated from differences of total pressure before and behind the model (in wake) using rake probe, Fig 4.

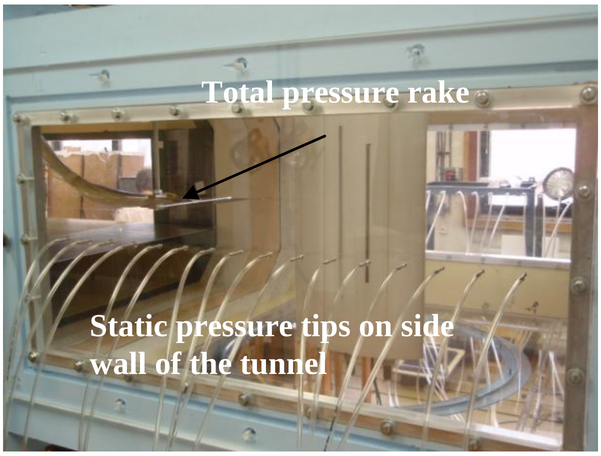

Fig. 3 Position of the model in wind tunnel

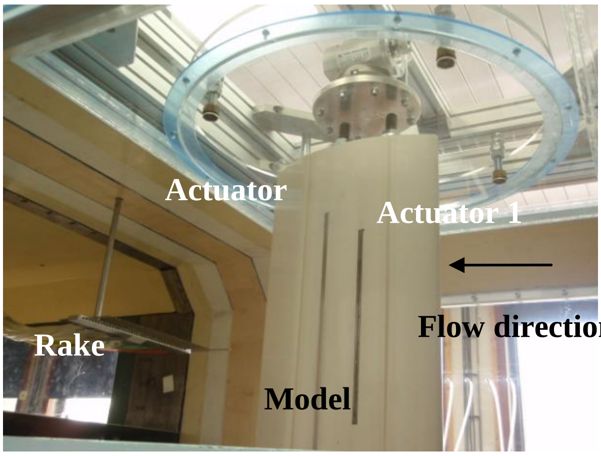

Fig. 4 Position of the actuators on the model

3 Results

In Fig. 5 there is clearly visible the influence of synthetic jets to the direction of the flow and size of the wake. Actuator 1 is in position to influence size of separation bubble. Effect of Actuator 1 is clearly visible on both the change of lift coefficient and drag coefficient, Fig. 5 and Tab 3. Size of wake is smaller and position of wake was moved about 17 mm, which corresponds to the change of angle about 3.5°.

The effect of Actuator 2 to the change of drag coefficient is minor comparing with Actuator 1 with respect to its lower intensity. This is caused due to very low intensity of synthetic jet. If we look to the Tab. 2, it is clearly visible very low value of output mean velocity (about 6 m.s^{-1}) from the synthetic jet generator comparing to mean flow field velocity. Value of momentum coefficient c_μ (about 0.02 %) for Actuator 2 is lower than its recommended minimal value (about 0.04 %).

Maximal change of drag coefficient c_D is about 20% and maximal change of lift coefficient c_L is about 4.5% for both actuators.

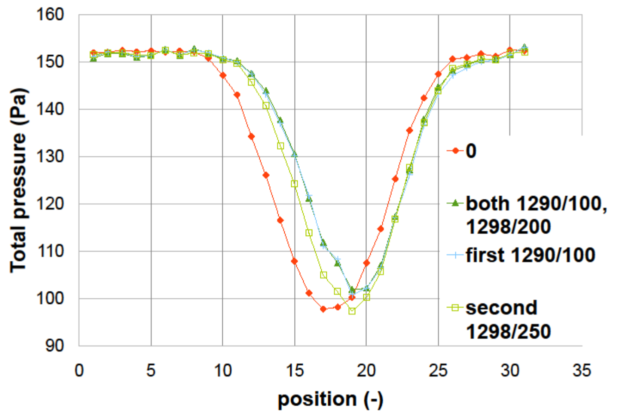

Fig. 5 Development of total pressure in wake behind profile

Actuator 1	Actuator 2	Δc_L (%)	Δc_D (%)
1290/100	1298/200	3.51	20.79
1295/300	1295/300	4.53	18.40
1290/100	0	2.24	17.95
1290/300	0	4.59	15.85
0	1298/250	4.04	13.68

Table 3 Influence of exciting frequencies to change of lift coefficient c_L and drag oefficient c_D

4 Discussions

In certain cases of application of flow control, it is necessary to consider not only the positive effect of this method, but also the required power supply, i.e. to consider the overall efficiency of the flow control. It is important to consider the efficiency of flow control in relation to the power input P_{in} of synthetic jet generator (flow control power supply devices) As regards the input of flow control power supply devices, the input power coefficient can be defined as, [2]:

$$c_E = \frac{P_{in}}{\frac{1}{2}\cdot\rho\cdot A\cdot U_\infty^3} \tag{6}$$

The sum of drag coefficient c_D and efficiency coefficient c_E result in a new value of drag coefficient c_{DE} and from this airfoil power efficiency η as, [2]:

$$\eta = \frac{c_L}{c_{DE}} \tag{7}$$

Values of airfoil power efficiency and input power coefficient are in details in Table 4. There is clearly visible that effective is Actuator 1. Value of power efficiency of Actuator 1 is the highest. Actuator 2 has lower power efficiency. This is caused due to very low momentum coefficient c_μ of Actuator 2.

Actuator 1	Actuator 2	c_D	c_{DE}	η (%)
1290/100	1298/200	0.074	0.093	6.8
1295/300	1295/300	0.079	0.104	6.0
1290/100	0	0.076	0.088	7.3
1290/300	0	0.077	0.088	7.1
0	1298/250	0.081	0.095	6.6
0	0	0.095	-	7.0

Table 4 Influence of exciting frequencies to change of drag coefficient c_D and airfoil power efficiency η

5 Conclusions

Reduction of drag coefficient and positive change of lift coefficient were obtained in all cases – application Actuator 1 and 2. Taking consideration the value of power input of the actuators and extend of influence of the synthetic jets to the flow field can be detecting low efficiency of second actuator.

With respect to very low momentum coefficient c_μ of Actuator 2 there isn't clearly visible a positive effect of exciting frequency using modulated signal applied for turbulent boundary layer flow control. For the first actuator there is positive effect of amplitude modulation to the size of separation bubble.

Acknowledgment

The work has been supported by the project of Progressive Technology System for Power Engineering 1M06059, by the Ministry of Education, Youth and Sports of the Czech Republic No. 1M06031. Grant support from GA of the Czech Republic 101/08/1112 and GA AS of the Czech Republic No. IAA2076403 is also gratefully acknowledged.

References

[1] Lin J.C.,: Review of research on low-profile vortex generators to control boundary layer separation. *Progress in Aerospace Sciencies 38,* 2002, p. 389-420

[2] Glezer, A. and Amitay, M. 2002 Synthetic jets. *Annu. Rev. Fluid Mech.* 34, 503–529

[3] Uruba V.: On a synthetic jet flow, *GAMM Annual Meeting 2005* – Luxembourg, 20 Dec 2005

[4] Wygnanski I., Boundary layer and flow control by periodic addition of momentum, *49th AIAA Shear Flow Conference,* Snowmass, USA, June 29–July 4, AIAA Paper 972117, 1997

[5] Seifert A., Bachart T., Koss D., Shepshelovitch M., Wygnanski I., Oscillatory blowing: a tool to delay boundary-layer separation, *AIAA J. 31* (11) (1993) 2052–2060.

[6] Greenblatt D., Darabi A., Nishri B., Wygnanski I., Separation control by periodic addition of momentum with particular emphasis on dynamic stall, *Heli Japan 98,* American Helicopter Society, Gifu, Japan, April 1998, paper T3–4.

[7] M. Matejka, P. Pick, P. Prochazka and J. Nozicka, Experimental Study of Influence of Active Methods of Flow Control on the Flow Fileld Past Cylinder, JFVIP, February 2010

[8] M. Matejka, P.Pick, Effect of Amplitude Modulation of Synthetic Jet Excitation Signal on Flow Control, Experimental Fluid Mechanics 2009, 25 – 27 November, Liberec, Czech Republic

[9] Greenblatt D., Wygnanski I. J.: The Control of Flow Separation by Periodic Excitation. *Aerospace Science 36 (2000),* pp. 487-54

[10] Matejka M., Popelka L., Safarik P., Nozicka J.: Separation control by synthetic jet actuator in a straight blade cascade. 26th ICAS - Proceedings, Anchorage, USA, 2008, ISBN 0-9533991-9-2

[11] Popelka, L., Wind Tunnel Test Section for Aifoils and Bodies, Research Programme Feasibility Studies. Proceedings of the Conference Topical Problems of Fluid Mechanics 2008, Institute of Thermomechanics AS CR , Prague, 2008, pp. 85-88.

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