An Experimental and Analytical Investigation of Aerodynamic Flow Control Using Synthetic Jet Technology

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Abstract

Synthetic jet is well known as a novel method of active flow control. The core of technique is synthetic jet actuator. In order to make certain the actuation conditions, hot wire anemometry is used to measure the velocity in the flow from the actuator. And then the experiment using synthetic jet to fulfill the airfoil flow control is performed. The results show that stalling characteristic is improved, and maxim lift coefficient is improved on a certain extent. At last, problems in experiment are discussed.

1. Introduction

Methods for flow control can be classified into groups: passive or active[1]. Vortex generators, riblets, large-eddy break-up devices, castellation and passive cavities are belonged to passive control system, and cannot adapt to changes in the incoming flow. But active control systems can operate optically at a range of conditions making them more flexible than passive control systems. The current active control systems are as follows: deforming surfaces, variable velocity jets, pulsed jets, active suction and bleed.

Synthetic jet ("zero-net-mass-flux"[2]) is well known as a novel method of active flow control. In 1994, the actuator (see Figure 1) designed by Smith and Glezer in Georgia Institute of Technology is used successfully to flow control and this experiment arouses extensive attention. The mechanism and application of synthetic jet actuator is gradually investigated hotspot. Synthetic jet tends to produce highly localized flow control. The actuators are compact and require small amount of power to operate, which can be easily housed inside the vehicle whose aerodynamic characteristics are supposed to modify. So they have emerged as one of the most useful mico-fluidic devices with potential application ranging from thrust vectoring jet control[3], mixing enhancement[4] to active control of separation and turbulence in boundary layers[5,6].

The purpose of this paper is to investigate the flow control effectiveness of a synthetic jet actuator mounted along the chord of a YLSG107 airfoil. In order to make certain the actuation conditions in this experiment, hot wire anemometry is used to measure the velocity in the flow from the actuator. And then the experiment is conducted in a NWPU Aerodynamic Design and Research Center low-speed wind with 3 x 1.6 m test section. The aerodynamic effect is investigated with synthetic jet actuation at different chordwise locations, under different freestream velocities. At last, problems in the experiment are discussed.

2. The Actuator and Experimental Setup

The synthetic jet actuator consists of a membrane at the bottom of a small cavity, which has an slot in the face opposite the membrane. In the current design, the cavity is cylindrical and communicated to the ambient fluid through a rectangular slot, 0.5mm in width. The length of the rectangular slot is l =36mm and thickness is t =1.6mm. The cavity is made by stainless steel and the inner surface of which is required to get some extent coarseness grade.

The planform of the actuator is shown in Figure 2.

The membrane with coil in magnetic field is forced to oscillate by AC signal which is generated by the variable frequency wave generator and amplified by the power amplifier circuit. The working voltage of the power amplifier circuit is supported by DC regulated power supply. In the whole experiment, the driving voltage virtual value and its waveform loading to the coil are respectively monitored by the digital multimeter and oscillograph, so this can get real-time monitoring and insure the reliability of experiment.

A small, single element hot-film probe is used to measure the velocity in the flow emanating from the actuator, and the probe signals are acquired and reduced using a TSI-IFA300 data acquisition unit, which can operate conventional statistic such as the time-average, standard deviation and power spectrum from the reduced velocity signals. The data are acquired at a sampling rate of 10000/sec, for a period of 0.8192 sec. The probe is mounted on a traverse and placed normal to the actuator, with its sensing element parallel to the exit slot.

The two-dimensional YLSG107 airfoil model has the dimension of 1.59 m span and 1.0 m chord, and the synthetic jet actuator is installed across the airfoil span at one of four different chordwise locations for the test. These four actuator locations are at x/c=0.175, 0.325, 0.525, and 0.725. One of the test purpose is to determine the optimal placement of the actuator on the airfoil. In order to avoid the actuator cavity contaminated, the slot of actuator is usually sealed without use. So the YLSG107 airfoil model is shown in Figure 3.

3. Establishment of Reasonable Actuation Conditions

In order to get obvious control effect in this experiment, it is imperative that the velocity characteristics of actuator be carefully investigated. The actuator is excited with different excitation waves and frequencies, the velocity near slot is measured by the hot-film probe. So it can find reasonable actuation conditions with airfoil experiment.

The velocity output from the actuator is decided by the geometry size of actuator, excitation waveform and frequency, and is highest when it is excited at its resonant frequency. The vibrating disk can be modeled as a circular plate, rigidly clamped at its edge. The solution to this problem is well documented[7], and it indicates that the two resonance frequencies are gotten. The centerline velocity at distance of X/d=2 (d means width of slot) from the slot exit is measured at various excitation frequency from 20 Hz to 2000 Hz (see Figure 4). It shows that the mean velocity peaks at its resonance frequency, and the mean velocity is higher when the actuator is excited with a square wave, relative to the sinusoidal excitation. Two resonance frequencies of f_1 =475 Hz and f_2 =1700 Hz are easily identified. The actuator is excited at a resonance frequency of 1700 Hz with the square and sinusoidal waves, and the corresponding maximum mean velocity is respectively 4.70 m/sec and 3.91 m/sec. It is important to note that the actuator can produce fairly high velocities, even when operate off-resonance.

For protection of the vibrating membrane and more energy supplying the boundary layers, the actuator of airfoil experiment is excited with a sinusoidal wave at frequency of 400Hz, and the corresponding maximum mean velocity is 3.718 m/sec.

4. Results and Discussion

The purpose of experiment is comparison of airfoil performance between synthetic-jet-on and synthetic-jet-off at the same position. Due to the experiment with synthetic-jet-off we adopt two different projects.

Project one is that experiment with synthetic-jet-off is operated with all sealed slot. The experiment with synthetic-jet-on is operated at different position. But the experiment is only operated with one synthetic jet every time, and the rest slots are sealed. Figure 5 shows lift curve at V_∞ = 45 m/sec (freestream velocity).

The results show that stalling characteristic is improved, and are consistent with the experiment operated by McCormick[8]. Table 1 represents the result of experiment with different chord, and shows that the maxim lift coefficient is improved most obviously at the position of $x/c = 0.175$ on the whole.

Project two is that the experiment with and without synthetic jet is operated with only one unsealed slot at different position. The two cases are also equivalent to airfoil with slot. Figure 6 shows lift curve at V_∞ = 30 m/sec (freestream velocity). It is clear that the stalling characteristic is improved. The outcome is consistent with project one. Table 2 and table 3, which represent the result of experiment without and with coarse strip at the position of $x/c =$ 0.175, show the maxim lift coefficient is influenced by synthetic jet. These results show that maxim lift coefficient is improved on a certain extent. The experimental effect is related to the conventional momentum coefficient C_u, that is a function of the airfoil chord, freestream velocity, slot width and jet velocity.

The conventional momentum coefficient C_u, is introduced in detail by Smith et al[9], the ratio of the synthetic jet momentum flux to the freestream momentum flux, and defined as

$$C_u = \frac{2\rho_j U_j^2 b}{\rho_0 U_0^2 c}$$

where ρ_j and ρ_0 are the jet and freestream fluid densities, respectively, U_0 is the freestream velocity, and U_j is the averaged jet velocity measured at X/d=2 (d means width of slot). The airfoil experimental effect is related to this conventional momentum coefficient. The value of the coefficient is bigger, and the flow control effective is better[9]. In this study, C_u is too small. So the flow control effective is not obvious.

5. Summary and Conclusions

The results in this experiment show that the synthetic jet actuator designed here is helpful to improve the stalling characteristic, and the maxim lift coefficient is improved on a certain extent. The experimental effect is not specially evident, because energy supplied to boundary layer is not enough. At last, problems in the experiment are discussed. The effect on airfoil separation flow control is related to such factors (i.e. maxim velocity generated by actuator, the selected airfoil, the actuator installed position, and slot vertex angle). In order to obtain satisfactory results, the experiment on airfoil separation flow control with synthetic jet actuators is needed to consider all factors.

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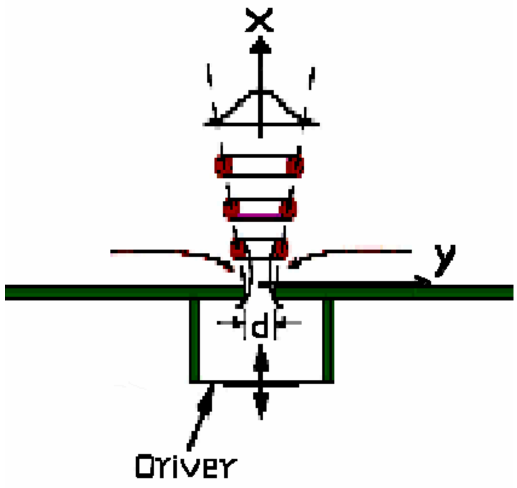

Fig.1 Schematic drawing of the actuator

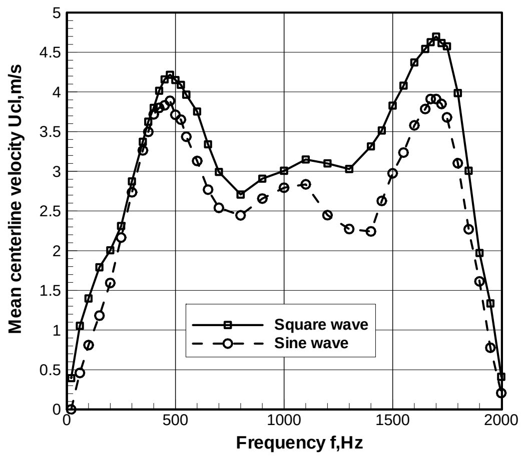

Fig.4 Mean centerline velocity at a distance of X/d=2 from the slot exit

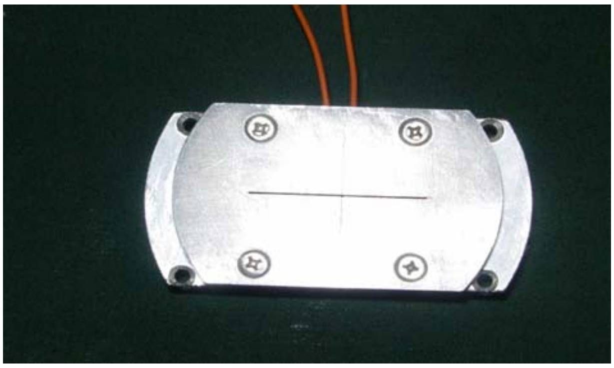

Fig.2 Object of the synthetic jet actuator

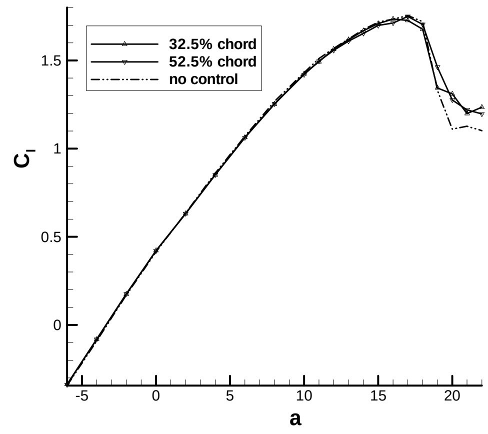

Fig.5 C_l performance with synthetic jet at different position（V_∞ =45m/sec）

Fig.3 Photograph of YLSG107 airfoil

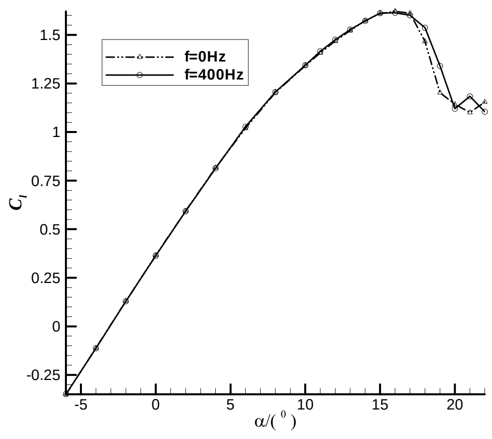

Fig.6 C_l performance with coarse strip at the position of $x/c = 0.175$

Table 1 The comparison of $C_{l\,\max}$ synthetic jet at different chord

Control / V_∞	Off	On			
		x/c=0.175	x/c=0.325	x/c=0.525	x/c=0.725
15 m/sec	1.4973	1.5112	1.5101	1.5105	1.5058
30 m/sec	1.6145	1.6351	1.6213	1.6247	1.6364

Table 2 The comparison of $C_{l\,\max}$ without coarse strip

Control / V_∞	Off	On
10 m/sec	1.4837	1.5376
15 m/sec	1.5292	1.5330
20 m/sec	1.5362	1.5475

Table 3 The comparison of $C_{l\,\max}$ with coarse strip

Control / V_∞	Off	On
10 m/sec	1.4555	1.4829
15 m/sec	1.4900	1.5039
20 m/sec	1.5361	1.5349