Chinese Journal of Aeronautics, (2016), **29**(2): 346–357

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Experimental investigations for parametric effects of dual synthetic jets on delaying stall of a thick airfoil

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Received 12 February 2015; revised 6 July 2015; accepted 20 November 2015
Available online 24 February 2016

KEYWORDS

Active flow control;
Airfoil;
Dual synthetic jet arrays;
Flow separation;
Stall

Abstract A promising strategy of synthetic jet arrays (SJA) control for NACA0021 airfoil in preventing flow separation and delaying stall is investigated. Through aerodynamic forces, flowfield and velocity profiles measurements, it indicates that the synthetic jet (SJ) could enlarge the mixing of the shear layer and then enhance the stability of boundary layer, resulting in scope reduction of the flow separation zone. Furthermore, the control effects of dual jet arrays positioned at 15%c (Actuator 1) and 40%c (Actuator 2) respectively are systematically investigated with different jet parameters, such as two typical relative phase angles and various incline angles of the jet. The jet closer to the leading edge of airfoil is more advantageous in delaying the stall of airfoil, and overall, the flow control performances of jet arrays are better than those of single actuator. At the angle of attack (AoA) just approaching and larger than the stall AoA, jet array with 180° phase difference could increase the lift coefficient more significantly and prevent flow separation. When momentum coefficient of the jet arrays is small, a larger jet angle of Actuator 2 is more effective in improving the maximum lift coefficient of airfoil. With a larger momentum coefficient of jet array, a smaller jet angle of Actuator 2 is more effective.

1. Introduction

The flow separation and stall lead to lift decrease of airfoil, and thus, limit flight speed envelope and improvement of aerodynamic performance of aircraft.[1] Active flow control (AFC) has been one of the most promising methods for improving aerodynamic characteristics of airfoil, and further expanding operating envelope of aircraft.[2–5] As a novel AFC method, synthetic jet has been confirmed to be an efficient technology

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Peer review under responsibility of Editorial Committee of CJA.

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http://dx.doi.org/10.1016/j.cja.2016.02.010
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to control flow separation and stall of airfoil at different status.[6–9] Though synthetic jet introduces zero net-mass-flux into fluid flows, it provides effective unsteady momentum addition in the form of vortex pairs or vortex rings without the bulk and cost of the steady sources.[10]

In order to disclosure control mechanism of synthetic jet on delaying flow separation and stall of airfoil, Seifert et al. conducted active control experiments on NACA0015 airfoil, and the capability of synthetic jet on delaying stall of airfoil was verified.[11] Several experimental results have indicated that synthetic jet localized near the location where flow separation forms can significantly enhance aerodynamic characteristics of airfoil, including increment of maximum lift and stall angle.[12–17]

According to the investigations about control effects of jet location on airfoil performance, jet arrays containing two or more actuators placed at different chord positions were designed to further delay stall of airfoil. Hassan carried out numerically investigation on stall control of airfoil via jet array with two actuators,[18] and the simulated results preliminarily indicated that jet array helps to further improve aerodynamic characteristics of airfoil. Regrettably, the two jet actuators with one pulsed suction jet and the other pulsed blowing jet turned on alternately; as a result, the interactions of the two jets were not taken into account. Additionally, experimental investigations on airfoil stall and flow separation control using synthetic jet arrays were carried out to further analyze the characteristics of jet arrays.[19,20] The experimental results preliminarily showed that the synthetic jet arrays (SJA) had potential in delaying flow separation and improving aerodynamic performance of airfoil than single jet. However, the investigations of these references focused on the control effects of jet arrays with fixed few parameters and the aerodynamic interaction between jet actuators was ignored. At the same time, there is still a lack of research on the influence of control effects due to varied parameters of jet array.

In order to better understand parametric effects of jet array, Lee et al. experimentally investigated separation control for an inclined flat plate by jet arrays with varied parameters.[21] The results indicated that the location and phase of a synthetic jet array may be essential for flow separation control effects. Unfortunately, the investigations on airfoil stall control via jet array were not carried out, so Lee pointed out that control effects of dual jet array on airfoil should be further investigated to understand the separation control mechanism of jet arrays.

Until now, the control mechanisms of the interaction between different actuators of jet array are not clear yet, there is still a lack of parametric analyses of jet array control on airfoil stall and flow separation in particular.[22,23]

In this paper, to further explore the physical understanding of flow control effects on airfoil via jet arrays, comprehensive experimental investigations have been conducted on synthetic jet array control of NACA0021 airfoil. The tests include aerodynamic force and flowfield measurements in wind tunnel. Furthermore, in emphasis, parametric analyses of jet arrays on stall and flow separation control effects are carried out, especially two typical jet phase difference and a series of relative jet angles between different jet actuators, and some valuable conclusions are obtained, which help to better understand the regularity of jet array control on stall of airfoil and provide foundations for further parametric optimization design of jet array.

2. Experiment platform and procedure

2.1. Airfoil model and synthetic jet array

In the present experiments, the 1-inch full range speaker units are designed as jet actuators, and three typical jet directions are achieved using different covers with varied jet angles, see Fig. 1. The actuators are placed at 15%c (Actuator 1, A1) and 40%c (Actuator 2, A2) of airfoil respectively.

Considering the size of actuators, and the installation of the actuator arrays in airfoil model, NACA0021 airfoil is employed in the experiment. The parameters of experimental airfoil (wing) model and jet actuators are shown in Table 1.

Fig. 2 shows that the root mean square (RMS) velocity varies with the excitation frequency f at the centerline of jet orifice of an isolated actuator according to different excitation voltages. As shown in the figure, the RMS velocity of jet increases with a larger excitation voltage U_{jet}, and there is a peak RMS velocity when the excitation frequency is about 200 Hz (which is adopted in the whole test). In addition, the differences among jet velocity with different jet angles θ_{jet} are very small; for unity, the variation of the jet velocity with the excitation voltage is taken the average of the three cases.

2.2. Measuring equipment

The tests of synthetic jet array control for large flow separation of airfoil in stall are conducted in low-speed return flow wind-tunnel (with a circular experimental section) of Nanjing University of Aeronautics and Astronautics. The experiments include aerodynamic force measurements of airfoil, flow velocity measurements over airfoil by particle image velocimetry (PIV) technology and evaluation of velocity profiles in boundary layer. System for measurement of aerodynamic force

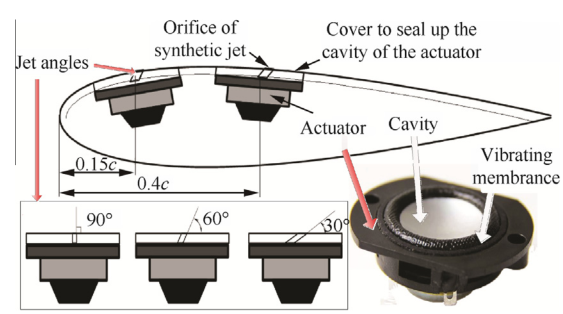

Fig. 1 Jet actuators and their installation in airfoil (wing) model.

Table 1 Parameters of airfoil model and jet actuators.

Parameter	Value
Chord × span (mm)	200 × 360
Width × length of jet orifice (mm)	1.5 × 20
Jet angle (°)	30, 60, 90
Chordwise location	15%c, 40%c
Size of jet actuator (mm^3)	43 × 35 × 16
Resistance of actuator (Ω)	4
Rated power of actuator (W)	5