29th Congress of the International Council
of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

THE EFFICIENCY ANALYSIS OF GUST ALLEVIATION BASED ON ACTIVE FLOW CONTROL

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Keywords: *numerical simulation, active flow control, gust response, gust alleviation*

Abstract

The feasibility and efficiency of gust load alleviation is presented in this paper based on active flow control (AFC) technique. Numerical simulations are conducted to investigate the beneficial effects on the aerodynamic characteristics of the NLR airfoil using the AFC technique and conventional control surface during the gust process. Based on unsteady Navier-Stokes equations, the grid-velocity method is introduced to simulate the gust influence, and an unsteady suction/blowing boundary condition is enforced over a user specified portion of the airfoil's surface to emulate the AFC actuator. Firstly, the efficiency of gust load alleviation with flap deflection is verified. Furthermore, with the introduction of kinds of AFC technique, it is demonstrated that significant and gradual aerodynamic alternations are obtainable in the gusty flow, and the influence of AFC parameters are also conducted. And the physical analysis of the influence on gust alleviation is proposed to provide some guide for practice. Our results have indicated that the AFC technique, as a new technology of gust load alleviation, with the appropriate AFC parameters design, can effectively affect and suppress the fluid disturbances caused by gust, which is equivalent to the conventional flap deflection.

1 Introduction

The gust, also known as sudden wind, is a random wind disturbance with great strength in the atmosphere of nature. When the aircraft encounters the gust, additional unsteady aerodynamic forces and moments generate, and it can affect different aspects of the aircraft's operation, such as its dynamic loads, flight stability and safety. According to the disturbance suppression theory, it is necessary to generate the inverse aerodynamic force during the gust process to improve the aircraft performance, but it is impossible to implement in actual aircraft systems [1]. It is common for aircraft to utilize conventional trailing edge surfaces or spoilers to unload the aerodynamic disturbance caused by gust. For example, by actuating the ailerons in a symmetrical manner in the trailing edge up position, the lift on the wing is reduced and can even allow for a net downward load on the portion of the wing spanned by the aileron, thereby alleviating the effects of a gust load. But the drawback is that it would produce a certain delay time with the movement of control surface, and on the other hand the movement of control surface could not effectively suppress the impact of gust load on the aircraft. Also it can be noted that the conventional control surfaces start to lose effectiveness at higher angle of attack because of flow separation. Therefore, there is a need for exploring the new way of gust alleviation.

Currently, the AFC technique is a main focus in aeronautics. Via injecting a small amount of energy into regional or key areas, we can obtain local or global changes with fluid dynamic interaction, so as to achieve the purpose of improving the macroscopic flow characteristics.

With rapid development of micro/nano and MEMS technology, the miniaturization of AFC actuator technology has been mature in the manufacturing and can be widely used in control of micro/macro scale flow. The AFC technology, with the advantage of small, light, energy-efficient, fast response and significant control effect, has a broad prospect in improving the aerodynamic performance of aircraft and flight. There have been numerous studies on the AFC actuator design, the flow field characteristics, formation mechanism and initiatives carried out in the application of aircraft [2-3].

The basic concept behind the control techniques implemented and analyzed in these studies is that small and localized active pneumatic control can sufficiently modify the global parameters of the flow (lift, drag, noise, signature, stability, etc.) with little additional energy consumption. In this way, AFC has been employed on two dimensional airfoils to change the surface pressure distribution, increase the lift, reduce the drag at high angles of attack, and so delay the flow separation [4-8]. When the jets issue from the leading edge of the airfoil, the jet flow interacts with the separated shear layer and changes the aerodynamic shape of the flow surface affecting the pressure distributions on the airfoil. The shear layer then either remains attached to the airfoil over a longer distance relocating the separation point, or the separated shear layer reattaches on the airfoil as the transfer of high momentum fluid to the surface by jet interaction.

In the experiment of Hassan[9], the studies have shown that the AFC technique, with the arrangement of zero-mass-jet actuator on airfoil surface, can achieve the aerodynamic performance of aileron deflection, but the authors omitted the presentation of the flow control efficiency in the real atmosphere, such as gusty flowfield.

In essence, the gust is disturbance of atmospheric, and the gust response can be considered as the follow-up development processes of steady flow state with disturbance while the aircraft encountering the gust. And for the AFC technology, it is also the fluid interference between the mainflow and jet flow. Therefore, theoretically, the AFC technology can be introduced for gust alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed by AFC technology.

The current work is a continuation of the studies initiated in Ref [10-12] to develop a sustained and practical flow/flight control system for unmanned aerial vehicle (UAV) operating in a gusty environment. In our previous research, we validate the feasibility of gust load alleviation based on conventional control surface [10], and then the efficiency is analysis for the three-dimensional UAV [11]. At the follow-up study [12], we provided the first demonstration of the gust load alleviation based on the AFC technology corresponding to the airfoil, and the results have indicated that the AFC technique was effective for aerodynamic load alleviation in the gusty environment. This successful application of AFC opens new vistas in the technology of gust load alleviation using novel fluid dynamic concepts.

In this paper, the effectiveness of gust alleviation based on AFC technique is analyzed for the NLR air foil, and the comparison of alleviation efficiency with conventional control surface is also conducted. The aerodynamic force histories and pressure distributions are examined to study and explain the characteristics of gust response and gust alleviation.

The ultimate goal is to generate the adequate control force and replace the traditional control surface with AFC technology, we intended to realize the practical application of AFC technology and provide some guidance for the future work.

2 Computation Scheme

2.1 Governing Equation

The CFD computations are conducted using a developed time dependent, viscous compressible Reynolds-averaged Navier-Stokes flow solver [10]. The spatial discretization involves a semi-discrete finite-volume approach. Roe’s flux difference splitting scheme is choosing for the convective and pressure terms, while the central differencing is used for the shear stress and heat transfer terms. Time advancement is implicit with the ability to solve steady and unsteady flows. The Spalart-

Allmaras turbulence model is selected for numerical investigation, and the multigrid is used for convergence acceleration.

2.2 Gust Model

In this paper, the gust is simplified as discrete model with only vertical disturbance. As illustrated in Fig.1, the aircraft cruises with the free stream velocity v_∞ initially, and then suddenly passes through the gusty flowfield with the vertical speed w_g . For simplify, we neglect the degree of freedom of the aircraft, and just considered the aerodynamic response without the motion of the aircraft.

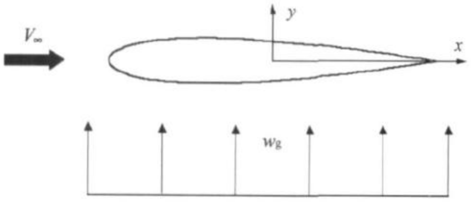


Fig. 1 Skematic of gust leading a step change in angle of attack

Unsteady simulations are written to incorporate the grid-velocity method, which is used to model unsteady flow via grid movement[13]. Physically, grid velocity can be thought of as the velocity of a grid element during the motion of the airfoil. Therefore, the method is to add the gust velocity over the entire flow domain instead of only at the airfoil surface to simulate the gust excited unsteady flow. For example, for the gust profile shown in Fig. 1, the step change in the angle of attack is identical with a step change in vertical velocity all over the flow domain. In addition, this method does not produce any numerical oscillations and produces results that agree exceedingly well with the exact solutions available in the initial stages [12-15].

2.3 AFC Model

To model the perturbation on the flow from the harmonic motion of the actuator, a suction/blowing type boundary condition is used for the five kinds of flow control technique such as steady blowing, steady suction, unsteady blowing, unsteady suction, and synthetic jet[16]. As show in Fig.2, the perturbation on the flowfield is introduced through the wall component of velocity prescribed at the surface for simplify. The velocity boundary conditions is given by

$$V_{jet}(t) = V_0 + V_a \sin(\Omega_{jet} t) \qquad (1)$$

Where V_0 represents the steady velocity component, V_a is the unsteady velocity component, and Ω_{jet} is the oscillation frequency. In the array region, all jets are assumed to operate in unison with same phase, and all jets are also assumed to have same instantaneous velocity given by the above equation [6, 17].

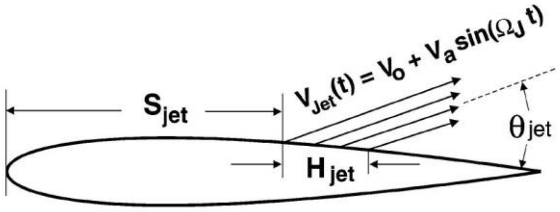


Fig. 2 Schematic of unsteady boundary conditions for flow control on airfoil

2.4 Incorporation of CFD Method

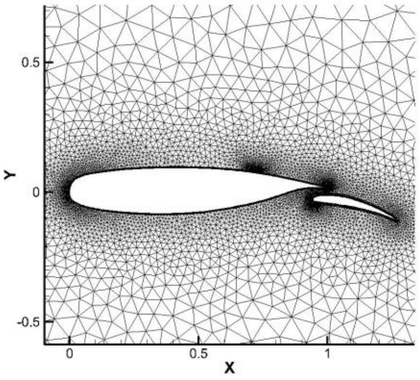
In the present work, an incorporated method has been implemented into the CFD solver[12]. Firstly, the steady flowfield of airfoil is obtained and used for the initial condition of the unsteady simulation. Then within the gust response simulation progress, the flow field disturbance caused by gust is transferred directly to the flow control equation in the form of incremental velocity vector over the entire flow domain, as aforementioned solution process, the AFC model is set to the boundary condition of no-slip wall. Further, the jet is modified by using suction/blowing boundary condition prescribed at the airfoil surface. Starting from the initial steady results, obtained by the AFC model and the gust model considered, we will propose a simultaneously solution progress, and this could be considered as an incorporated method that can be conveniently used in preliminary research and synthesis of control authority for gust load alleviation based on AFC technique.

3 Results and Discussion

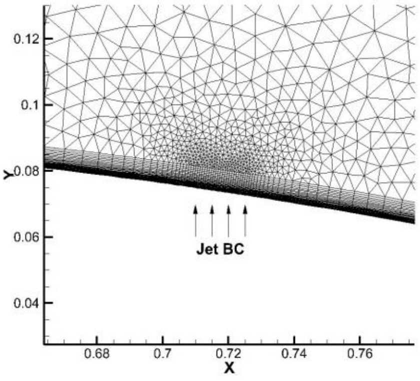
3.1 Computational Model

The two-dimensional NLR airfoil is selected to research gust alleviation based on the flow control technique. First, the aerodynamic characteristics of airfoil is analysis under typical gust model, then the efficiency of gust alleviation is present with the different flap movement model, finally, with the introduction of different AFC technique, the performance of gust alleviation is compared with the flap movement.

The computations are performed using a hybrid grid in Fig.3. In the boundary layer zone, the structured grid is used to solve flow viscosity with a minimum normal spacing of 5.0×10^{-6} c (c represents the chord of airfoil), and the unstructured grid is used for the outer zone to realize flap movement with dynamic mesh technique. The jet at the slot is resolved using a fine grid consisting of twenty-five grid points for the width of 1.5%c on the location of 0.71c.



(a) grids of airfoil



(b) grids around jet boundary-condition(BC)

Fig. 3 Schematics of computational grid with velocity boundary condition for airfoil

Fig.3 shows the computation grid and enlarged view near the flow control jet.

3.2 Analysis of Gust Responses

The time-dependent aerodynamic force response is conducted with the vertical gust depicted in Fig.1, and the vertical speed is choosing $0.08v_\infty$. In Fig.4, at the initial stage of the gust process, the lift show sudden step up in all calculated Mach numbers, then abruptly drop in a very short time and the final result eventually reach steady states. Take the state of *Ma*=0.30 for example, the lift of steady state is 2.01, and within the gust process, the peak lift is 3.32 at small times, the final steady lift coefficient is 2.62. It can be concluded that the aerodynamic response of airfoil is significant during the gust process, and the aerodynamic interference of gust cannot be ignored.

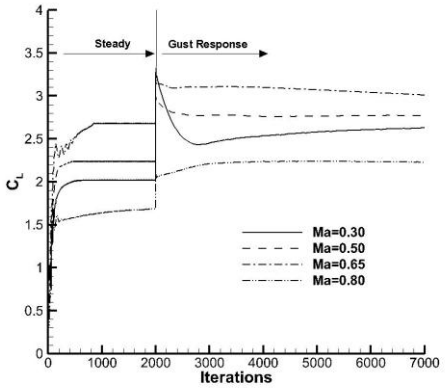


Fig. 4 Indicial lift response at various Mach numbers

3.3 Analysis of Gust Alleviation with Flap Movement

Further we investigate the efficiency of gust alleviation with the conventional control surface deflection, the aerodynamic disturbance generated by designed movement is used to affect and suppress the gust load. The flap deflection model is defined as follows:

$$\alpha(t)=\alpha_0+\alpha_m\sin(\omega t) \tag{2}$$

Where a_0 represents the initial angle of flap, a_m the maximum deflection angle, and ω the deflection angular velocity. The influence of flap motion control parameters is analyses under the flow condition of *Ma*=0.30.

The effect of the maximum deflection angle on the aerodynamic performance is presented here. In Fig.5, it shows the efficiency of gust load alleviation with $\omega = 1800^{\circ}/s$ and $a_m = 4^{\circ},8^{\circ},10^{\circ}$. It can be conducted that, with the increase of a_m, the effect of gust load alleviation gradually increased, with the $a_m = 10^{\circ}$, the finally stable of the lift coefficient is coincided with the steady state.

Next, the effect of the deflection angular velocity is discussed. Fig.6 shows the efficiency of gust load alleviation with flap motion control parameters $a_m = 10^{\circ}$ and $\omega = 500^{\circ}/s, 1000^{\circ}/s, 1800^{\circ}/s$, it can be found that the larger angular velocity represent the quick response and better efficiency of gust load alleviation.

Specific computations are performed at free stream Mach numbers of 0.50 and 0.80 with flap motion control parameters $a_m = 10^{\circ}$ and $\omega = 1800^{\circ}/s$. Figure.7 shows the instantaneous lift coefficient comparison of gust response and gust alleviation. It indicates a gradual and desired trend of the gust load alleviation, and with the higher Mach numbers, the less efficiency of flap motion is observed due to the smaller aerodynamic disturbance.

The results presented above show the global effect of gust load alleviation with the flap movement, and the flap motion control parameters have the powerful influence for the gust alleviation.

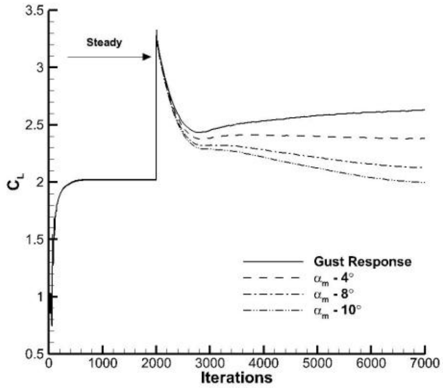


Fig. 5 The gust alleviation results for various of flap angle at Ma=0.30

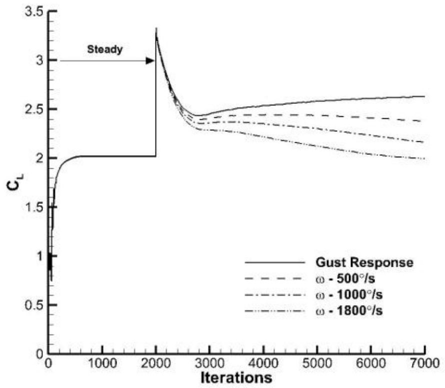


Fig. 6 The gust alleviation results for various of flap angular rates at Ma=0.30

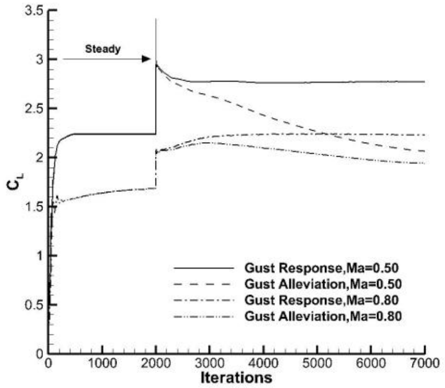


Fig. 7 The gust load alleviation results for various of mach numbers

3.4 Analysis of Gust Alleviation with AFC

3.4.1 Efficiency of Gust Load Alleviation with Kinds of AFC

The following subsections discuss the effects of gust alleviation with the AFC technology, and the comparison of gust alleviation with flap movement is also present. The aerodynamic characteristic of airfoil with gust profile of Fig.1 is analyzed in cruise state of Ma=0.3, $\alpha = 3^{\circ}$. Three kinds of AFC methods, steady blowing, steady suction and synthetic jet, are introduced. For the AFC model, the peak velocity v_a is 25m/s, and the oscillation frequency Ω_{jet} is 1500Hz. For the flaps deflection model, the maximum deflection angle a_m is 5 deg and 10 deg, the deflection angular velocity ω is $200^{\circ}/s$. Fig.8 describes the time history of airfoil lift characteristics considering the implementation of flow control methods during the gust process. Note that the effect of using conventional flap is also included in Fig.8, where the flap is deflected at 5 deg and 10 deg.

It is easily noticeable that the steady suction results in hardly any measurable change in the lift characteristics of the model, whereas the steady blowing, at the same momentum coefficient, provides a significantly larger effect, note that the steady blowing method reduces the amplitude of the lift up to 19%, it is comparable to flap deflection of 7~8 deg, which is more than enough to alleviate the gust load.

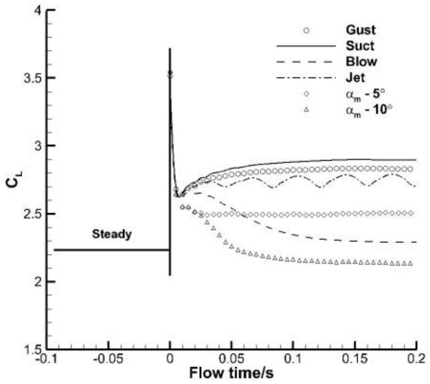


Fig.8 The efficiency of gust alleviation with three AFC methods

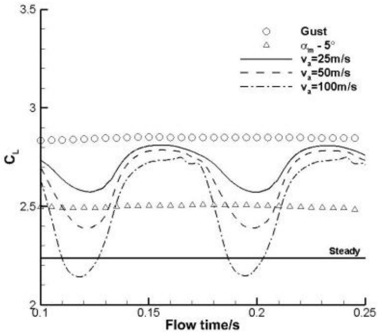
3.4.2 Influence of the Flow Control Parameters

With the pre-basis research, the synthetic jet technique is choosing for the further exploration. The following subsections discuss the effects of the AFC parameters, and the result of 5 deg of flap deflection is used for comparison. And for the AFC parameters, the actuator jet peak velocity is 25m/s, 50m/s and 100m/s, the jet frequency 750Hz, 1500Hz, 3000Hz.

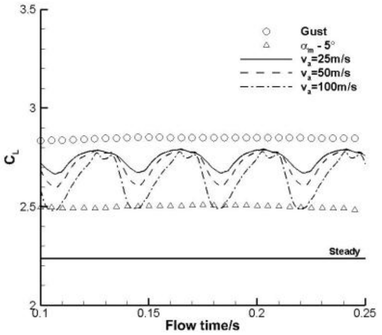
The effect of the jet velocity on the aerodynamic performance of the NLR airfoil is presented here. Fig.9(a)、(b) and (c) present the change(with respect to the baseline) in the lift coefficients, respectively, at the different jet frequency, when compared with the lift authority due to the 5 deg flap deflection.

Fig.9(a) presents the control power with different jet velocity at the same jet frequency of 750Hz, where the activation of the synthetic jets yields a noticeable change in lift coefficients. An average lift coefficient of 2.41 at the jet velocity v_a of 100m/s can be noted over the entire control range, this is comparable with a flap deflection of 6~7 deg, according to the 5 deg and 10 deg flap deflection data. Also note the highly desirable induced trend of increasing the control authority of the AFC-induced lift coefficient as the jet velocity increases. This is because the fluidic excitation level is more energetic with the increased jet velocity, increasing the excitation momentum and control authority.

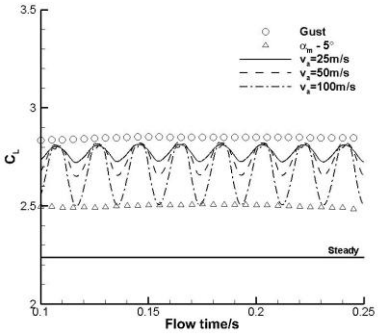
In Fig.9(b) and 9(c), the higher jet frequency of 1500Hz and 3000Hz is presents; in each of these figures three jet velocities are also considered. For all three jet velocities the use of



(a) f=750Hz



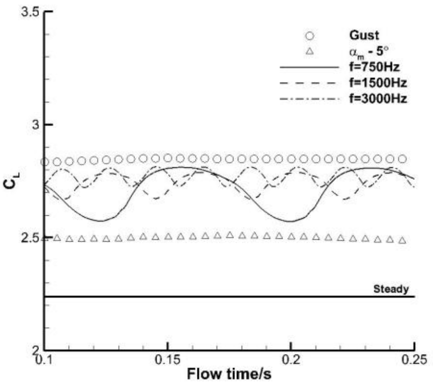
(b) f=1500Hz



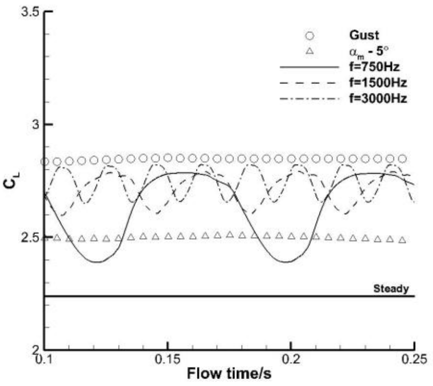
(c) f=3000Hz

Fig.9 The efficiency of gust alleviation with jet velocity synthetic jet results in noteworthy gust load alleviation. Here the efficiency of gust alleviation is shifted towards higher jet velocity, where at the v_a of 25m/s and 50m/s the lift coefficient change is decreased.

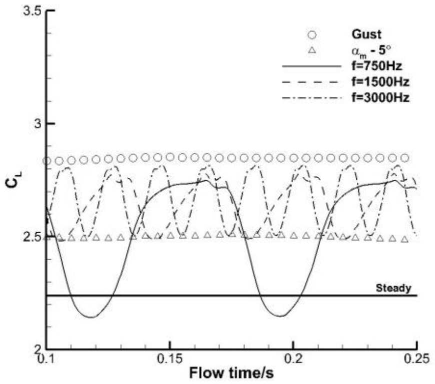
A representative result regarding the effectiveness of jet frequency is presented in Fig.10. In this case the gust load alleviation effect with flap deflection of 5 deg is also investigated. For all the three figures, it is observed that lower jet frequency is more effective at the change of lift. Take Fig.10(a) for example, a slight change in time averaged lift coefficient is observed as jet frequency of 3000Hz with a local peak jet velocity of 25m/s, and lower jet frequency results in obvious gust load alleviation. And this trend of lift coefficient is also qualitatively similar to the previous results.



(a) $v_a = 25\,m/s$



(b) $v_a = 50\,m/s$



(c) $v_a = 100\,m/s$

Fig.10 The efficiency of gust alleviation with jet frequency

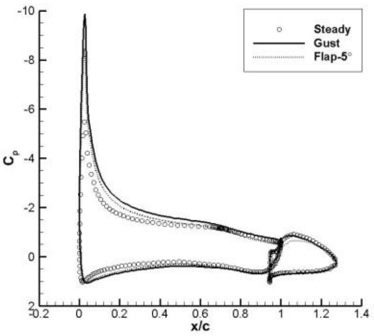
In this particular case, it is suggested that the lower excitation frequency or the higher jet velocity of the synthetic jet is seen to be more effective at generating control authority and result in a more efficient actuation.

3.4.3 The Mechanism Analysis of AFC

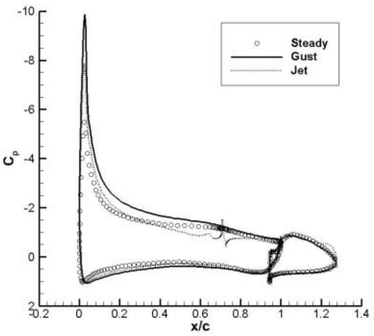
To further explore the effect of the AFC technology for gust alleviation, distribution of the time-averaged pressure coefficient around the airfoil for different gust alleviation technology is shown in Fig.11 (a) and (b), respectively. The pressure distribution for the steady flow (marked with blanked circle) and gusty flow (marked with solid line) are also shown for reference.

When encountering the gust, the angle of attack of airfoil has a sudden increase, the pressure change near the leading edge area is significant. In Fig.11, the gust results in a sharp suction peak pressure coefficient at the leading edge, the degree of pressure recovery towards the trailing edge of the airfoil is reduced.

For the conventional flap deflection, the distributions of pressure coefficient exhibit lower suction peak than the gusty flow and consequently a decrease in the lift coefficient. After the arrangement of synthetic jet actuator on the trailing edge of airfoil, the jet interaction with the flow around the airfoil affects the pressure distribution to some degree, and thus achieves the purpose of gust load alleviation, and the efficiency is more comparable to the 5 deg of flap deflection. The overall integrated effect on aerodynamic performance is strongly dependent on the nature of the local interaction between the actuators and the embedding flow.



(a) The efficiency of flap deflection



(b) The efficiency of synthetic jet

Fig.11 The comparison of time-averaged pressure coefficient with different gust alleviation technology

Therefore, the AFC technology, via injecting a small amount of energy into regional or key flow areas, can affect and suppressed the fluid disturbances caused by gust. And with the appropriate control parameters, flow control technology can be effectively used for gust load alleviation, which is equivalent to the conventional flap deflection.

4 Conclusions

A CFD method is presented in the paper to simulate the gust alleviation based on AFC technology. The feasibility of this technique is verified and the efficiency of gust load alleviation is conducted with different active flow methods. The results show that:

(1) With the grid-velocity method, it is easy to apply the gust boundary conditions for the gust response simulation. The boundary conditions, specified as the unsteady suction/blowing velocity of the jets, can effectively simulate the flow disturbance caused by actuators.

(2) The conventional flap movement can significantly reduce the lift response, and the gust alleviation effect can be controlled by flap deflection parameters.

(3) The predictive work showed that the AFC technology, as a new developing approach for the future application of vehicle aerodynamic control, can be effectively used for gust disturbance suppression and gust load alleviation. The most significant finding is the degree to which vary the AFC authority compared to the conventional flap deflection, not only are the flow control technologies of the change affected, but also are the flow control parameters of the change.

(4) Authors had presented the numerical simulation of gust alleviation based on AFC, but the efficiency of practical application is also an outstanding performance parameter which is need to fully understand and shall be presented in the future work to give more relevance to the study. A great attention must be paid to the experiment and three-dimensional configuration, since this would then provide a more holistic understanding of the predictive application in practical aircraft.

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Acknowledgments

The paper is supported by National Natural Science Foundation of China(11302178，11202162), Aeronautical Science Foundation of China(2013ZA53002), NPU Foundation for Fundamental Research(JCT20130110).

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