Application of Active Flow Control Technique for Gust Load Alleviation

XU Xiaoping\textsuperscript{a}, ZHU Xiaoping\textsuperscript{b}, ZHOU Zhou\textsuperscript{a,*}, FAN Ruijun\textsuperscript{a}

\textsuperscript{a}National Key Laboratory of Science and Technology on UAV, Northwestern Polytechnical University, Xi’an 710072, China

\textsuperscript{b}Research Institute of Unmanned Aerial Vehicle, Northwestern Polytechnical University, Xi’an 710072, China

Received 28 July 2010; revised 23 February 2011; accepted 25 April 2011

Abstract

A new gust load alleviation technique is presented in this paper based on active flow control. Numerical studies are conducted to investigate the beneficial effects on the aerodynamic characteristics of the quasi “Global Hawk” airfoil using arrays of jets during the gust process. Based on unsteady Navier-Stokes equations, the grid-velocity method is introduced to simulate the gust influence, and dynamic response in vertical gust flow perturbation is investigated for the airfoil as well. An unsteady surface transpiration boundary condition is enforced over a user specified portion of the airfoil’s surface to emulate the time dependent velocity boundary conditions. Firstly, after applying this method to simulate typical NACA0006 airfoil gust response to a step change in the angle of attack, it shows that the indicial responses of the airfoil make good agreement with the exact theoretical values and the calculated values in references. Furthermore, gust response characteristic for the quasi “Global Hawk” airfoil is analyzed. Five kinds of flow control techniques are introduced as steady blowing, steady suction, unsteady blowing, unsteady suction and synthetic jets. The physical analysis of the influence on the effects of gust load alleviation is proposed to provide some guidelines for practice. Numerical results have indicated that active flow control technique, as a new technology of gust load alleviation, can affect and suppress the fluid disturbances caused by gust so as to achieve the purpose of gust load alleviation.

Keywords: active flow control; gust response; gust alleviation; numerical simulation; aerodynamics; unsteady flow; airfoil

1. Introduction

The gust, also known as sudden wind, is a certainty wind disturbance with great strength in the atmosphere. When the aircraft encounters the gust, additional unsteady aerodynamic forces and moments generate, and the aircraft flight performance is affected adversely. According to the disturbance suppression theory, it is necessary to generate the inverse aerodynamic force during the gust process to reduce the impact of gust load. And this is impossible to implement in actual aircraft systems\textsuperscript{[1]}. At present, the practical gust alleviation technique can handle the control surfaces to unload the aerodynamic disturbance caused by gust, such as flaps, ailerons, elevators, etc. As a result, it would produce a certain delay time with the movement of control surface; on the other hand this movement could not effectively suppress the impact of gust load on the aircraft. Therefore, it is necessary to explore a new way of gust alleviation.

Currently, active flow control (AFC) is an important research area in fluid dynamics. We can use fluid dynamic interaction between the fluids to obtain local or global changes in the flow via injecting a small amount of energy into regional or key areas, so as to achieve the purpose of improving the flow characteristics of aircraft. With rapid development of modern micro-
With the development of computational fluid dynamics (CFD) technology and computer performance, numerical calculation has already been carried out for aircraft gust response research. Unsteady Euler equations have been applied to determine directly the indici responses and gust responses of an airfoil in compressible flow. The values of initial and final stages of the indici responses closely match the exact analytical values given by piston theory and quasi-steady airfoil theory [2-3]. Singh and Baeder used a modified unsteady Euler solver to calculate the indici response of a rectangular wing to a step change in the angle of attack. This advanced method employed the grid time metrics including the velocity change in the angle of attack. This advanced method has a broad prospect of application in improving the aerodynamic performance of aircraft and flight performance.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

At present, with the development of computational fluid dynamics (CFD) technology and computer performance, numerical calculation has already been carried out for aircraft gust response research. Unsteady Euler equations have been applied to determine directly the indici responses and gust responses of an airfoil in compressible flow. The values of initial and final stages of the indici responses closely match the exact analytical values given by piston theory and quasi-steady airfoil theory [2-3]. Singh and Baeder used a modified unsteady Euler solver to calculate the indici response of a rectangular wing to a step change in the angle of attack. This advanced method employed the grid time metrics including the velocity change in the angle of attack. This advanced method has a broad prospect of application in improving the aerodynamic performance of aircraft and flight performance.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

At present, with the development of computational fluid dynamics (CFD) technology and computer performance, numerical calculation has already been carried out for aircraft gust response research. Unsteady Euler equations have been applied to determine directly the indici responses and gust responses of an airfoil in compressible flow. The values of initial and final stages of the indici responses closely match the exact analytical values given by piston theory and quasi-steady airfoil theory [2-3]. Singh and Baeder used a modified unsteady Euler solver to calculate the indici response of a rectangular wing to a step change in the angle of attack. This advanced method employed the grid time metrics including the velocity change in the angle of attack. This advanced method has a broad prospect of application in improving the aerodynamic performance of aircraft and flight performance.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.

In essence, the gust is disturbance of atmospheric, and the aerodynamic response can be considered as a follow-up development process of stable flow states with disturbances around the aircraft while encountering the gust. Therefore, theoretically, active flow control technology can be used for gust load alleviation. It means that the fluid disturbances caused by gust can be affected and suppressed through active flow control technology during the gust process to achieve the purpose of gust load alleviation.
not only encounters a sudden change, but also couples with the angular velocity of pitch. As a result, the calculated response is not a pure step change in angle of attack \(^{2-3}\). Grid-velocity can be treated as the velocity of a grid point during the unsteady motion caused by gust. This method incorporates a step change into the entire flow domain as input parameter. 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. That is, the airfoil is exposed only to a pure change of angle of attack without pitch rate. This results in a decoupling between time histories of the angle of attack and the pitch rate.

2.3. Active flow control model

Generally, there are two ways to set active flow control boundary conditions: flow flux mass and flow velocity. For the sake of consistency, this paper uses regular velocity boundary condition for the five kinds of flow control technique such as steady blowing, steady suction, unsteady blowing, unsteady suction, and synthetic jet \(^{17}\). As show in Fig. 3, the jet is modified by using suction and blowing velocity boundary condition prescribed at the surface. The velocity boundary conditions is given by

\[
V_{jet}(t) = V_0 + V_a \sin(\Omega_{jet}t)
\]  

where \(V_0\) represents the steady velocity component, \(V_a\) the unsteady velocity component, and \(\Omega_{jet}\) the oscillation frequency. In the array, all jets are assumed to operate in unison with no phase shift. All jets are also assumed to have the same instantaneous velocity given by the above equation\(^{12,18}\).

2.4. Incorporation of CFD method

At first, the airfoil steady flow field is solved and used for the initial calculation of the unsteady simulation. Then for the gust response simulation, the flow field disturbance caused by gust is transferred directly to the flow control equation in the form of incremental velocity vector. As aforementioned solution process, the jet is set to the boundary condition of no-slip wall. Further, when considering the gust alleviation analysis based on active flow control technique, the jet is modified by using suction and blowing velocity boundary condition prescribed at the surface, then the simultaneously solution progress, gust model, active flow control model and flow field solution model, are achieved.

3. CFD Code Validation

3.1. Unsteady method validation

Turbulent flow past a NACA0012 airfoil sinusoidal oscillating in pitch at the 1/4 chord is modeled to validate the CFD method. The angle of attack of the airfoil is governed by

\[
\alpha = 4.86 \chi + 2.44 \sin(2\pi \kappa t L_{ref}),
\]

where the non-dimensional frequency \(\kappa\) is 0.015 47, and \(L_{ref}\) represents the airfoil chord. The instantaneous lift coefficient \(C_L\), pitching moment coefficient \(C_m\) variation curve of airfoil at instantaneous angle of attack in oscillation period comparing with experimental data\(^{19}\) are shown in Fig. 4. Because of hysteresis of unsteady
flow, the unsteady periodic solutions of lift and moment coefficient are shaped as hysteresis loops.

### 3.2. 2D gust model validations with theory

As the gust profile shown in Fig. 1, the NACA0006 airfoil is used for program verification. The C-type mesh consists of 181 grid points in the chord-wise direction, and 51 grid points along the direction normal to the foil surface. The grid extends 20 times the chords behind the airfoil’s trailing edge. The steady state flow field at zero angle of attack is evaluated and serves as the initial condition for all the following simulations. All the following analyses are based on a non-dimensional time step of 0.01. Specific computations are performed at free stream Mach numbers \( (Ma_f) \) of 0.30, 0.50, 0.65, and 0.80. The gust response calculations are performed on the same airfoil with gust velocity equal to 8% of the free stream velocity, so that it induces a step change in angle of attack of approximately 4° in each case.

Fig. 5 shows the time history of the computed lift coefficient normalized by the angle of attack. In Fig. 5, \( S \) is non-dimensional time. The results show that the lift characteristic responses of the airfoil agree well with the calculated values in Ref. [2].

![Fig. 5 Comparison of lift characteristic response for gust with Ref. [2].](image)

According to the Indicial theory [2], the lift values of the initial stage match the exact linear piston theory values of \( 4/Ma_{\infty} \), while the lift values of the final stage are close to linearized steady state value of \( 2/(1 + Ma_{\infty}) \). Table 1 shows the comparison of the lift values predicted by the analytical theories and the lift magnitudes obtained using the CFD method. It can be found from Table 1 that the CFD results for the smaller time step are in good agreement with the values calculated for low Mach number. As the Mach number increases, the flow field tends to be nonlinear and the theoretical solutions based on the linearized compressible theory are quite different from the actual results.

<table>
<thead>
<tr>
<th>( Ma_f )</th>
<th>Exact results</th>
<th>CFD</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S=0 )</td>
<td>( S=50 )</td>
<td>( S=0 )</td>
<td>( S=50 )</td>
</tr>
<tr>
<td>0.30</td>
<td>13.33</td>
<td>6.58</td>
<td>12.92</td>
</tr>
<tr>
<td>0.50</td>
<td>8.00</td>
<td>7.25</td>
<td>7.70</td>
</tr>
<tr>
<td>0.80</td>
<td>5.00</td>
<td>10.47</td>
<td>4.62</td>
</tr>
</tbody>
</table>

Lomax has derived exact closed form expressions of the indicial responses for short time for a flat plate airfoil in linearized compressible flow [5]. The expression is given by

\[
C_L(s) = \frac{4}{Ma_{\infty}} \left[ 1 - \frac{1}{1 + Ma_{\infty}} \right] s
\]

Fig. 6 shows a comparison of the computed and exact results at small times. It can be seen that the agreement is excellent. It should also be noted that since the exact solutions are based on linear theory, the agreement is expected to be progressively worse for higher Mach numbers, the comparison is excellent for \( Ma_{\infty}=0.30 \), while the agreement reduces progressively through \( Ma_{\infty}=0.80 \).

![Fig. 6 Comparison of computed and exact results.](image)

### 4. Results and Discussion

The quasi “Global Hawk” airfoil is selected to take the initiative to research gust alleviation with flow control technique. The computations are performed using a 417×129 C-grid with a minimum normal spacing of 5.0×10⁻⁶c (c represents the chord of airfoil). The jet at the slot is resolved using a fine grid consisting of 25 grid points for the width of 1% c. Fig. 7 shows the computational grid and enlarged view near the flow control jet.

#### 4.1. Analysis of gust responses

The vertical gust depicted in Fig. 1 shows the time-dependent aerodynamic force responses for a variety of Mach numbers. In Fig. 8, at the initial stage
of the gust process, the lift coefficients show sudden step ups in all calculated Mach numbers, then abruptly drop in a very short time, and eventually reach steady states. Take the state of $Ma_f=0.30$ for example, the lift coefficient of steady state is 0.5511, and within the gust process, the peak lift coefficient is 1.5433 at small times, and the final steady lift coefficient is 1.0775. 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.

4.2. Analysis of gust alleviation

At first, the aerodynamic characteristic of airfoil with gust profile of Fig. 1 is analyzed in cruise state of $Ma_f=0.60$, $Re=1.5\times10^5$, $\alpha=1^\circ$. Three kinds of active flow control methods, steady blowing, steady suction and synthetic jet, are introduced. The peak velocity $V_a$ is 10 m/s, and the oscillation frequency $\Omega_{jet}$ is 1 500 Hz. Fig. 9 describes the time history of airfoil lift characteristics considering the implementation of flow control methods during the gust process. The steady suction has little impact on airfoil lift characteristics, but the steady blowing method and synthetic jet method have significant effects on gust load alleviation, and the steady blowing method reduces the amplitude of the lift up to 17.67%.

Fig. 10 presents the comparison of airfoil pressure distribution for different flow control methods at the non-dimensional time $S=100$. In Fig. 10, $C_p$ is the pressure coefficient. When encountering the gust, the angle of attack of airfoil has a sudden increase, the pressure change near the leading edge area is signifi-
cant, the area increase in leading edge suction zone and pressure zone leads to increase of lift coefficient. After the arrangement of flow control 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.

Moreover, the gust alleviation effects are analyzed with half-wavelength 1-cos gust profile, and additional flow control methods, unsteady blowing, unsteady suction are introduced. In Fig. 11, the lift coefficient time history of airfoil with five active flow control methods is compared during the gust process. All five flow control methods are effective for gust load alleviation to some extent. The steady/unsteady blowing methods have the most obvious alleviation effect, followed by synthetic jet method, and steady/unsteady suction method is relatively weak.

Fig. 12 shows the time averaged flow field characteristics of different flow control methods. As can be seen from the figure, when the gust is applied to the airfoil, the angle of attack increases, and the flow field tends to separate at the trailing edge. The blowing control method further enlarges the separation region of the trailing edge, thus reducing the lift; the synthetic jet method and suction method can control the separation characteristics, thus partly alleviating the perturbation brought by gust. In general, the gust changes the initial flow field characteristics around the airfoil, and the designed flow control method can effectively affect and suppress the gust load, so as to maintain the steady flow field.

5. Conclusions

A CFD method is presented in the paper to simulate the gust alleviation based on active flow control. The feasibility of this technique is verified and the gust load alleviation efficiency of different active flow methods is conducted.

With the grid-velocity method introduced in gust response simulation, it is easy to apply the gust boundary conditions. And this hardly causes additional numerical oscillations. The active flow control boundary conditions, specified as the velocity in the jets, can effectively simulate the flow disturbance caused by flow control actuators.

Numerical simulations of gust response for the quasi "Global Hawk" airfoil show that gust would cause significant changes in aerodynamic characteristics of airfoils. The gust load disturbances can be suppressed with active flow control techniques, and the analysis of airfoil surface pressure distribution also verifies the conclusions.

Our results suggest that the developed gust alleviation based on active flow control, with the careful selection of the control parameter, can be used for gust disturbance suppression and gust load alleviation. The important parameters which warrant further investigation are the jet angle, jet velocity and frequency.

References

[2] Parameswaran V, Baeder J D. Indicial aerodynamics in compressible flow-direct computational fluid dynamic


Biographies:

XU Xiaoping  Born in 1981, he received B.S. and M.S. degrees from Northwestern Polytechnical University in 2004 and 2007 respectively, and now he is a Ph.D. candidate. His main research interest is CFD and flight vehicle design. E-mail: xuran.npu@163.com

ZHOU Zhou  Born in 1966, she is a professor in Northwestern Polytechnical University. Her main research interest lies in flight vehicle design and flight control. E-mail: zhouzhou@nwpu.edu.cn