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Application of Active Flow Control Technique for Gust Load Alleviation

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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 [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-

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nano and MEMS technology, active flow control actuator miniaturization technology has been mature in the manufacturing and can be widely used in micro and macro-scale flow control. Active flow control technology, with low power consumption, fast response and significant control effect, 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 determining directly the indicial responses and gust responses of an airfoil in compressible flow. The values of initial and final stages of the indicial responses closely match the exact analytical values given by piston theory and quasi-steady thin airfoil theory [2-3]. Singh and Baeder used a modified unsteady Euler solver to calculate the indicial 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 caused by the impulsive change in the angle of attack, but the mesh was not moved accordingly [4]. Responses of discrete gusts of various shapes, amplitudes, and gradient lengths were computed via the reduced-order models and were compared with responses simulated directly by the CFD code [5]. Gust responses were analyzed with two degrees of freedom in plunging and pitching for the airplane with and without the consideration of structural deformation [6-7].

Several researchers have done much work on the active flow control actuator design, the flow field characteristics, formation mechanism and initiatives carried out in the application of flow control research [8-9]. In the airfoil flow control, researches have shown that active flow control technology has great development potential in being used to control separated flow of airfoil, increase the lift and reduce the drag [10-14]. In the experiment of Hassan, et al. [15], the studies have shown that active flow control technique, with the arrangement of zero-mass-jet actuator on airfoil surface, can achieve the aerodynamic performance of aileron deflection.

In this paper, a new gust alleviation technique based on active flow control technique and its feasibility is analyzed based on the quasi "Global Hawk" airfoil. First, the gust aerodynamic response of the airfoil is analyzed at different Mach numbers. And then active flow control technology is introduced. The impact of gust aerodynamic characteristics is studied with different flow control technologies.

2. Computation Scheme

2.1. Governing equation solver

The CFD computations are conducted using a developed Reynolds-averaged Navier-Stokes (RANS) flow solver [16]. The spatial discretization is accomplished by a cell centered finite volume formulation. Roe's flux difference splitting is used for the convective and pressure terms, while central differencing is used for the stress and heat transfer terms. Time advancement is made with a linearized backward Euler scheme with the ability to solve steady or unsteady flows, and the Spalart-Allmaras turbulence model is selected for numerical investigation.

2.2. Gust model

As depicted in Fig. 1, the aircraft cruises at free stream velocity V_∞ initially, and then suddenly passes through the gust flow with vertical speed w_g. According to the Indicial theory [2,4], it induces a step change in the angle of attack of $\Delta\alpha$ ($\Delta\alpha$ =arctan(w_g/V_∞)).

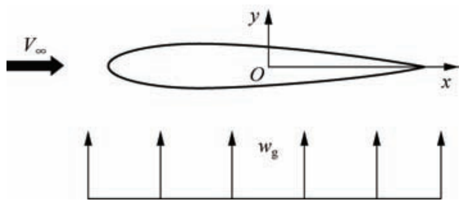

Fig. 1 Skematic of gust leading a step change in angle of attack.

Practically, the gust velocity changes with time and space. As shown in Fig. 2, the discrete gust with half wavelength one-minus-cosine (1-cos) profile can be expressed as

$$\begin{cases} w_g = 0 & x < 0 \\ w_g = \dfrac{1}{2}W_0\left(1-\cos\dfrac{2\pi x}{2H}\right) & 0 \le x \le W_0 \\ w_g = W_0 & x > W_0 \end{cases} \quad (1)$$

where W_0 is the designed cruise gust velocity, specified as 15.24 m/s with the altitude ranging from sea level to 6 km; the gust gradient length H is 12.5 times of the mean geometric chord lengths based on the experimental evidence [17]. The definition of non-dimensional time is S=2$V_\infty t/c$, where t is the time step, c the chord of airfoil.

The grid-velocity method is introduced to simulate the gust influence [2]. Take the airfoil encountering the gust shown in Fig. 1 for example, if boundary condition with sudden change of angle of attack is directly given to the airfoil, then the angle of attack of airfoil