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Gust response and body freedom flutter of a flying-wing aircraft with a passive gust alleviation device

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ABSTRACT

The effectiveness of a passive gust alleviation device (PGAD) mounted at the wingtip of aircraft in conventional and flying-wing configurations have been studied in previous research. However the PGAD influence on the aeroelastic stability in particular the body freedom flutter (BFF) of a flying-wing aircraft remains as a concern. This present investigation is focused on evaluating the beneficial effect of PGAD on both gust load alleviation and BFF of a small flying-wing aircraft of high aspect ratio wing made of composite. A small range of (1-cos) type of gust load has been considered to select a representative critical gust load case for the study. A parametric study indicates that there is a narrow band of optimal key parameters for the PGAD design. Subsequently a set of optimal parameters is selected to further the analysis of the PGAD mechanism. The case study results show that the PGAD can make the bending moment at the wing root due to gust reduced by 16%. In addition, the BFF speed of the flying-wing aircraft is increased by 4.2%. The investigation reveals that the PGAD mode and its interaction with the wing bending mode and short period oscillation of the aircraft can have beneficial aeroelastic effect on both gust alleviation and flutter suppression.

1. Introduction

In aircraft design, various active and passive gust alleviation technologies have been developed including the classical active control [1–4] and passive control methods [5,6]. The gust response of an aircraft of high aspect ratio wing is sensitive to the engine placement [7]. Some of the studies of particular interest include the aeroservoelastic analysis of B2 bomber [8], and the wingtip device of discrete and raked options for gust load alleviation [9]. In the last decade, the feasibility of a novel passive gust alleviation device (PGAD) has been investigated for unmanned and large civil aircraft [10–12]. The PGAD is mounted at the wingtip of a flying wing aircraft through a shaft and elastic hinge as illustrated in Fig. 1. In the previous research, a parametric study of the PGAD was performed to determine the rotation stiffness and the shaft location in front of the aerodynamic centre. The PGAD will twist nose down in response to a vertical gust excitation to alleviate the excessive aerodynamic force. The results indicated that a significant reduction of gust response in terms of wing deflection and bending moment was achieved. For an aircraft of tailless flying-wing configuration however, the flight stability control and body freedom flutter (BFF) are two critical concerns, which has been studied before [13–15]. The USAFRL sponsored BFF research program since 2005 has led to the demonstration of active control technology for BFF suppression and gust load alleviation of the flying-wing UAV X-56A. Similar to the X-56A, the wingtip section of a flying-wing aircraft with large swept angle and high aspect ratio wing plays a mixture role of aileron and tail-plane. When the PGAD is employed, the wingtip section becomes a flexible control surface of the mixed functions. When facing a vertical gust load, the PGAD will twist nose down like an aileron to reduce the gust induced aerodynamic force on the wing. In the same time, the negative twist of the PGAD will produce a positive pitching moment on the aircraft like a tail-plane function. This results in an increase of angle of attack of the aircraft and consequently aerodynamic force on the whole flying-wing aircraft. An optimal PGAD design will lead to a balanced rotation together with the wing twist due to static aeroelastic effect. On the other hand, the PGAD raises an additional uncertainty and concern on the aircraft aeroelastic stability in particular the BFF. This project is aimed to investigate the PGAD function for gust response reduction and BFF suppression of a flying-wing aircraft.

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Nomenclature

$\boldsymbol{M}, \boldsymbol{D}, \boldsymbol{K}$	the mass, damping and stiffness matrix of the aircraft structure respectively;
$\boldsymbol{x}$	the special displacement vector of the aircraft structure;
$\boldsymbol{F}_{\mathrm{A}}, \boldsymbol{F}_{\mathrm{g}}$	the unsteady aerodynamic force vector due to dynamic motion and gust load;
$\boldsymbol{q}$	generalized displacement;
$\bar{\boldsymbol{M}}, \bar{\boldsymbol{D}}, \bar{\boldsymbol{K}}$	generalized mass, damping and stiffness matrix of the wing structure respectively;
$\bar{\boldsymbol{Q}}$	generalized aerodynamic force matrix;
$\boldsymbol{\Phi}$	normal mode matrix of the aircraft structure;
q_∞	the aerodynamic dynamic pressure;
$\Delta \boldsymbol{p}$	aerodynamic pressure on the lifting surface element panel
$\boldsymbol{C}_{\mathrm{A}}, \bar{\boldsymbol{w}}$	aerodynamic influence coefficient matrix and downwash on the lifting surface element;
$\boldsymbol{A}, b$	the reference area and reference semi-chord of the wing;
U, U_{de}	gust velocity and design (derived) gust velocity according to CS-VLA;
L_g, S	gust gradient and the distance of aircraft penetrating into the gust profile;
f_g, k_g	equivalent gust frequency (Hz) and gust alleviation factor respectively;
$c, \bar{C}$	local geometric chord and mean chord of the wing.
$C_{\mathrm{L}}, C_{\mathrm{L}\alpha}$	lift coefficient and derivatives of the wing
$C_{\mathrm{m}}, C_{\mathrm{m}\alpha}$	pitching moment coefficient and derivatives of the wing
$C_{\mathrm{Lq}}, C_{\mathrm{mq}}$	derivatives of the lift and pitching moment coefficients to pitch angular velocity;
$V_{\mathrm{c}}, V_{\mathrm{D}}$	cruise speed and dive speed respectively;
$V_{\mathrm{f}}, f_{\mathrm{f}}$	flutter speed and frequency respectively.

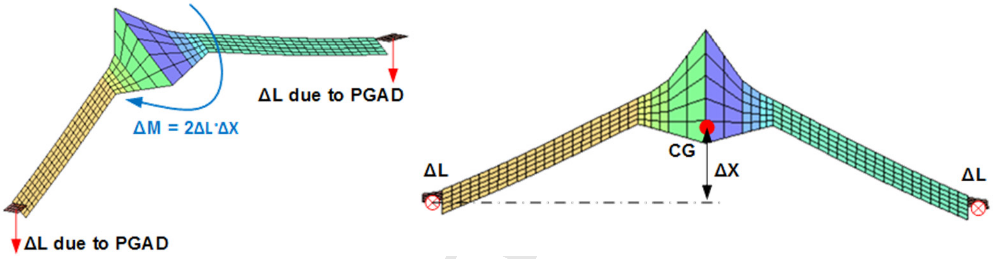

Fig. 1. PGAD mounted at the wingtip of a flying-wing aircraft.

The wing structure made of laminated composite is modelled using FEM; the aerodynamic analysis using doublet-lattice method; the aeroelastic analysis using P-K method based on normal mode in frequency domain respectively. The gust induced external aerodynamic force and response was based on the 1-*cosine* discrete gust model. In this study, the main concern is the relative gust response of an aircraft with the PGAD comparing with the baseline aircraft gust response without PGAD. Based on the modelling and analysis, a parametric study of the PGAD is carried out to determine the optimal design parameters for minimum gust response and maximum BFF speed. Taking a flying-wing aircraft model as a case study, the effectiveness of the PGAD is demonstrated by a significant reduction of the gust induced bending moment at the wing root. The optimal PGAD also makes beneficial contribution to the coupling between the short period oscillation and wing bending modes of the aircraft that leads to an increase of the BFF speed.

2. Analytical and numerical methods

A general form of the governing equation for aeroelastic analysis is expressed below.

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{D}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{F}_{\mathrm{A}} + \boldsymbol{F}_{\mathrm{g}} \tag{1}$$

where $\boldsymbol{M}$, $\boldsymbol{D}$ and $\boldsymbol{K}$ represents the mass, damping and stiffness matrix of the aircraft structure respectively; $\boldsymbol{x}$ represents the special displacement vector; $\boldsymbol{F}_{\mathrm{A}}$ and $\boldsymbol{F}_{\mathrm{g}}$ represents the unsteady aerodynamic force vector due to dynamic motion and gust load input. Since the PGAD is part of the wing structural, it is modelled as part of the $\boldsymbol{M}$ and $\boldsymbol{K}$ and also included in the $\boldsymbol{F}_{\mathrm{A}}$ and $\boldsymbol{F}_{\mathrm{g}}$ calculations.

By employing the normal mode method and generalized coordinate $\boldsymbol{q}$ into Eq. (1) to replace the $\boldsymbol{x} = \boldsymbol{\phi}\boldsymbol{q}$, the governing equation can be transferred from time-domain to frequency-domain and expressed by

$$\bar{\boldsymbol{M}}\ddot{\boldsymbol{q}} + \bar{\boldsymbol{D}}\dot{\boldsymbol{q}} + \bar{\boldsymbol{K}}\boldsymbol{q} - q_\infty \bar{\boldsymbol{Q}}\,\boldsymbol{q} = \Phi^T \boldsymbol{F}_g \tag{2}$$

where $\bar{\boldsymbol{M}}$, $\bar{\boldsymbol{D}}$ and $\bar{\boldsymbol{K}}$ represent the generalized mass, damping and stiffness matrix of the wing structure respectively; q_∞ is the dynamic pressure.

The unsteady aerodynamic force $\boldsymbol{F}_{\mathrm{A}}$ in the above equation is calculated using the Doublet-Lattice Method (DLM) built in the Nastran package. The aerodynamic pressure on the lifting surface element panels can be expressed in the following vector and matrix form,

$$\Delta \boldsymbol{p} = \frac{1}{2}\rho V_\infty^2 \boldsymbol{C}_{\mathrm{A}}^{-1} \bar{\boldsymbol{w}} \tag{3}$$

where ρ and V_∞ represents the air density and flight velocity of the aircraft respectively; $\boldsymbol{C}_{\mathrm{A}}$ represents the aerodynamic influence coefficient matrix; $\bar{\boldsymbol{w}}$ represents the downwash on the collocation points of the panel. The generalized unsteady aerodynamics in frequency domain can be calculated by

$$\bar{\boldsymbol{Q}}\,(k) = \boldsymbol{\phi}_{\mathrm{A}}^{\mathrm{T}} \boldsymbol{A} \boldsymbol{C}_{\mathrm{A}}^{-1} \left(i\frac{k}{b}\boldsymbol{\phi}_{\mathrm{c}} + \boldsymbol{\phi}_{\mathrm{c}}' \right) \tag{4}$$

where $\boldsymbol{\phi}_{\mathrm{A}}$ and $\boldsymbol{\phi}_{\mathrm{c}}$ are the mode shape at the aerodynamic centre and the downwash collocation point of the panel respectively; b and $k = \omega b/V_\infty$ is the reference semi-chord and a reduced frequency.

In the present study, the rigid body mode is included and the gust load $\boldsymbol{F}_{\mathrm{g}}$ is removed when performing BFF analysis. In the generalized coordinate system, the number of modes can be selected by truncating the high order modes according to the dominating modes in gust response and flutter analysis. The size of the Eq. (2) can be reduced significantly to save computational time.

In aircraft design, the gust velocity based on a discrete 1-*cosine* gust profile is expressed below.

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