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A novel yaw control method for flying-wing aircraft in low speed regime

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ABSTRACT

The innovative control effectors (ICEs) such as split drag rudder (SDR) or spoiler slot deflector (SSD) have been proved useful for the directional control of flying-wing aircraft. As opposed to the traditional rudder, the yaw control moment produced by a SDR is non-linear with respect to its deflection. The control reversal phenomenon arises at higher angle-of-attack in the low speed regime, causing unwanted directional oscillations. Such a behavior may lead to flight accident while landing or take-off. The aerodynamic efficiency of the SDR is investigated for a miniature flying-wing aircraft (XQ-6B) using computational fluid dynamics (CFD) approach. The classical unilateral SDR operating mode and the biased-differential SDR operating mode are presented and discussed. A novel control strategy based on the angle-of-attack feedback for the biased-differential deflection is proposed and verified in nonlinear numerical simulation. The results show that the non-linearity and control reversal problems present in the behavior of SDR can be alleviated with this scheme. Finally, the results obtained by testing the proposed technique in real low speed flight are presented in order to validate the improvements in the yaw control capability of SDR.

1. Introduction

The flying-wing aircraft is a novel design concept as compared to the conventional tube-and-wing aircraft. In a flying-wing aircraft design the fuselage and the wing both are integrated into a single all-wing body to achieve a better aerodynamic efficiency [1,2]. Modern flying-wing aircrafts are being designed with blended wing body (BWB) aerodynamic configuration, which provides many advantages, for instance, improving the whole vehicle's lift-to-drag ratio which results in extending aircraft range, reducing the radar cross section (RCS) etc. [3–8]. The downside of an all-wing aircraft design is the reduced directional stability and maneuverability due to the unavailability of a vertical tail and traditional rudder for yaw control [9–11]. Certain innovative control effectors (ICEs), such as split drag rudder (SDR) or spoiler slot deflector (SSD) have been proved useful for the yaw control of flying-wing aircraft in cruise state [12,13]. In a traditional aircraft, the yaw control is mainly achieved by modifying the camber of the vertical tail section by deflecting rudder, thus producing lateral aerodynamic force. Whereas, for the flying-wing aircraft, the yaw control moment is generated by the SDR (or SSD) which is proportional to the differential aerodynamic drag force between both sides of the wing [14,15]. In low speed high angle-of-attack flight condition like approach and take-off, the yaw moment produced by the SDR (or SSD) is inherently nonlinear with respect to control surface deflection and the control reversal phenomena appears at small deflection [16–18]. This control reversal phenomenon adversely affects the control capability of pilot or flight control system (FCS). Aircraft crash may occur if proper measures are not taken to mitigate such effects during landing or take-off, especially in presence of the crosswind.

In this article, a miniature unmanned flying-wing aircraft (XQ-6B) is developed to investigate and demonstrate the yaw control performance of the SDRs, while operating with the unilateral or multilateral mode. In modern aerodynamic design process of an aircraft, the computational fluid dynamics (CFD) approach is playing an increasingly important role, which reduces the wind tunnel experiment cost as well as the design cycle time. The basic aerodynamic characteristics of the XQ-6B and control efficiency of the SDR are studied via CFD analysis.

Recently, we have proposed a biased-differential configuration in order to bring improvements in the control efficiency of SDRs. In current work, a detailed study of this configuration is presented based on CFD simulation. It is found that the configuration can prove highly effective in low speed regime with the bias angle modulated with the angle-of-attack (AOA) feedback. Thus,

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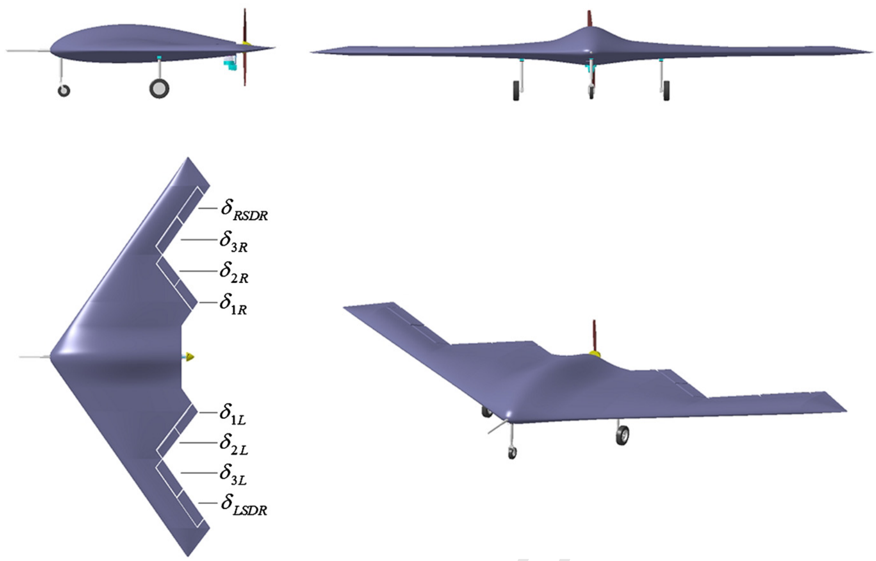

Fig. 1. XQ-6B UAV (side, front, top and 3D-view).

a novel control strategy named as SDR bias scheduling (SBS) is also presented and analyzed at low-speed flight conditions. A six-degree-of-freedom (6DOF) nonlinear dynamic simulation model is built using CFD aerodynamic data. The numerical simulation results show that with the proposed control strategy the intensity of nonlinear characteristics of the SDR is reduced effectively, and the directional control performance is improved remarkably in the low-speed regime. Finally, the proposed method is tested in the real flight to evaluate the yaw control performance. The results further validate the usefulness of the proposed method.

Rest of the paper is organized as follows. In section 2, important specifications are presented for XQ-6B aircraft's mechanical/aerodynamic design. In section 3, two different modes of SDR operation are discussed with necessary formulation. A detailed CFD based analysis of both modes of SDR operation is presented in section 4. In section 5, a complete control strategy is presented based on the SDR bias scheduling scheme. Results of nonlinear simulation and flight testing based on the proposed control strategy are presented in sections 6 and 7, respectively. The concluding remarks are given in section 8.

2. XQ-6B specification

A miniature flying-wing Unmanned aerial vehicle (UAV) named XQ-6B was developed by a research group of the Northwestern Polytechnical University, Xi'an. The maximum takeoff weight of the UAV is 20 kg with payload 3∼5 kg. The design cruise Mach number is 0.074, at an altitude of 1000 meters. A miniature four-stroke gasoline engine is mounted on the rear of the airplane, which can generate approximate 6 kg static thrust with a 2-blades fixed-pitch propeller. The XQ-6B UAV is design as a W-type flying-wing configuration without horizontal tail and vertical tail. The UAV looks like a B2 bomber, and the full-scale digital mock-up was created in CATIA software, as shown in Fig. 1. The main parameters of XQ-6B are listed in Table 1.

The XQ-6B consists of eight control surfaces at the trailing edge of the wing, namely, the inboard deflectors δ_{1L}, δ_{1R}, δ_{2L}, δ_{2R}, and outboard deflectors δ_{3L}, δ_{3R}, δ_{LSDR}, δ_{RSDR}. Each deflector is driven by a digital servo and can be controlled independently. The port SDR δ_{LSDR} and starboard SDR δ_{RSDR} mounted on the extreme outboard trailing edge of the wing are used for the yaw control of the tailless aircraft. Notable coupling effects on roll axis and pitch axis will be produced when the SDR is deflected. The range of

Table 1
Main parameters of XQ-6B.

	Parameter	Value	Unit
Platform	Wing area (S)	1.33	m^2
	Wing span (b)	2.77	m
	Mean aerodynamic chord (MAC)	0.65	m
	Leading edge sweep angle (Λ_L)	35	°
	Aspect ratio (λ)	5.6	
	Cruse speed (V_a)	25∼40	m/s
Power unit	Engine type	O.S. 155FS	
	Power output	2.6	hp
	Number of propeller blades	2	
	Propeller diameter	16	inch
	Propeller pitch	10	inch

control surfaces δ_{iL} $(i = 1, 2, 3)$ and δ_{iR} $(i = 1, 2, 3)$ are limited to $-30^\circ \sim 30^\circ$. While for the SDRs, the position limits are $0^\circ \sim 80^\circ$.

The longitudinal stability of XQ-6B is improved with aerodynamic optimization, such as the reflex airfoil is used in the inner wing and geometric twist is adopted for the outer wing, which can offer positive pitching moment [20]. Different from the conventional aircraft is that the longitudinal stability margin of the XQ-6B is designed with approximately 6% MAC, whereas the directional stability is almost reduced to neutral due to the absence of a conventional vertical tail.

3. SDR working principle

3.1. Classical mode

In classical unilateral SDR control mode, either of the two SDRs is deflected at a certain angle while the SDR on other side is held at zero degree, as shown in Fig. 2. This causes an imbalance aerodynamic drag force on the side of the wing whose SDR is deflected. Thus producing a yaw moment which turns aircraft nose to the direction of deflected SDR.

For the rudder deflection command δ_{SDR} at a given time t, the individual deflection of the starboard and port SDR can then be given by the following equations.

$$\delta_{RSDR} = \begin{cases} |\delta_{SDR}| & \delta_{SDR} < 0^\circ \\ 0 & \delta_{SDR} \geq 0^\circ \end{cases} \tag{1}$$

$$\delta_{LSDR} = \begin{cases} 0 & \delta_{SDR} \leq 0^\circ \\ |\delta_{SDR}| & \delta_{SDR} > 0^\circ \end{cases} \tag{2}$$

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