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Ground boundary layers effect on aerodynamic coefficients of a compound wing with respect to design parameters

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ABSTRACT

The ground viscous effect is an objective that could be an essential parameter for the conceptual design of wing-in-ground effect (WIG) crafts. This study numerically investigates the effect of ground boundary layers on the aerodynamics of a compound wing of a WIG craft. Computational simulations were conducted to evaluate various design parameters such as middle span size, anhedral angle and taper ratio. The flow structure in the physical domain around the wing surface was demonstrated with a realizable k-ε turbulent model. The numerical results of the compound wing for a fixed ground boundary condition were then further validated using experimental data from the wind tunnel. The principal aerodynamic coefficients of compound wings were achieved for both fixed and moving ground conditions. The numerical simulations demonstrated that the ground viscous effect of fixed ground has some effects on lift and drag coefficients and lift-to-drag ratio, including a reduction in the lift coefficient and an increase in the drag coefficient compared with the moving ground. However, the design parameters had a different impact on the ground viscous effect. Nevertheless, the results are predicted to be able to provide a more fine-grained understanding on the ground viscous effect on WIG craft.

1. Introduction

Aeronautical and maritime research groups are continuously investigating the wing in ground (WIG) effect in order to develop high-speed and efficient craft. The development of WIG craft was initiated in the early 1960s, but suffered from some operational issues such as power requirements and longitudinal stability during take-off. The ability to improve its efficiency compared to other types of craft and having a higher speed than other vessels are some reasons to consider WIG craft for marine transportation (Halloran and O'Meara, 1999). Besides, it comes with a low cost, does not require airports or runways, and is operational over any surface such as water or land (Rozhdestvensky, 2006). Increasing the ram pressure under the wing and decreasing the wing tip vortex are two techniques to improve WIG craft during service (Yun et al., 2010).

The pressure distribution around the wing is widely developed by the ground effect. The stagnation point moves to the lower surface of the wing, which leads to a larger amount of air diverting over the wing. Consequently, the speed of air flow on the lower surface decreases and pressure increases, creating a dynamic air cushion. At very low ground clearance, high pressure is created on the pressure side of the wing, referred to as ram pressure, and the lift achieves a noticeable improvement. Simultaneously, the downwash velocity reduces and causes a fall in the induced drag (Ahmed, 2004). The effective aspect ratio (AR) of the wing near the ground is greater than a geometric one (Yun et al., 2010). Ahmed and Sharma (2004) demonstrated that the convergent–divergent passage shape between the wing and the ground at certain angles of attack presented a suction effect that caused a reduction in lift. One particular method to decrease this phenomenon is via a flat surface on the lower side of the wing.

Luo and Chen (Luo and Chen, 2012) empirically investigated the pressure distributions cross-section of a NACA0015 wing and found that the pressure depended on angles of attack and ground clearance. However, at a negative angle of attack, the pressure had no ground clearance dependence. Jamei et al., 2012, 2013a numerically investigated the aerodynamic characteristics of a compound WIG effect. The compound wing was divided into two parts; the middle part as the rectangular wing and the side parts were reverse taper wings with an anhedral angle. They found that the compound wings significantly reduced the downwash velocity and modified the pressure distribution on the lower side, which led to augmentation in lift force. Moreover, the smaller distance between the wingtip of compound wings and the

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Nomenclature

a	Anhedral angle
b	Wing span
b_m	Middle wing span
c	Chord length
C_D	Drag coefficient
C_L	Lift coefficient
C_M	Moment coefficient
c_t	Tip chord length
D	Drag force
G_b	Generation of turbulence kinetic energy due to buoyancy
G_k	Generation of turbulence kinetic energy due to mean velocity gradients
h	Height of trailing edge above the ground
h/c	Ground clearance
k	Turbulent kinetic energy
L	Lift force
L/D	Lift to drag ratio
S	Wing planform area
S_{ij}	Mean rate of deformation tensor
U	Free stream mean velocity
u_j	Velocity in jth direction
Y_M	Effects of compressibility on turbulence
X_{CP}	Moment coefficient
ε	Turbulent energy dissipation rate
λ	Taper ratio (c/c_t)
μ	Air viscosity
μ_t	Turbulent viscosity
ρ	Air density

Acronyms

AOA	Angle of attack
CFD	Computational fluids dynamic
CO_2	Carbon dioxide
NACA	National Advisory Committee for Aeronautics
AR	Aspect Ratio
PAR	Power augmented ram
WIG	Wing-in-ground-effect

ground reduced the drag because of the weaker tip vortex. Jamei et al. (2011) investigated the performance, fuel consumption, and environmental impact of the compound wing. The lower drag of compound wings reduced the fuel consumption considerably. Relative to the rectangular wing the compound wing exhibited lesser CO_2 emissions.

Some researchers numerically investigated different arrangements of the PAR system on WIG craft (Yang and Yang, 2010, 2011). The aerodynamics of flow around the wings with respect to the nozzle angle PAR engine in front of the wing was analyzed by Yang and Yang (2011). They found that at a certain nozzle angle, the high-speed jet flow from the PAR system on the upper surface of the wing caused an increment in the suction and the separation moved toward the trailing edge. This is referred as to the Coanda effect.

Yang and Yang (2012) also numerically investigated the aerodynamics of a WIG effect with a tiltable endplate. They found that a tiltable endplate could potentially increase the performance of wings in and out of ground effect. Researchers acknowledge that ground boundary layers have some effects on the aerodynamics of the WIG effect. Yang, Yang, and Jia (Yang et al., 2010a) found a reduction of the effective height due to the rise of ground by using displacement thickness, which caused an over-estimation of ground effect. A separation bubble was created on the ground when the ground was considered a fixed boundary. This separation bubble rose with lower ground clearance and a higher angle of attack. Consequently, the passageway of air flow was reduced, which then reduced the ram effect, leading to underestimation of the lift. In addition, the separation bubble caused the stagnation point to move towards the leading edge, and then air flow on the upper surface of the wing gained higher energy with lower adverse pressure gradients, as there was a delay in the separation at the trailing edge and stall angle (Yang et al., 2010a). In contrast, Yang, Lin, and Yang (Yang et al., 2010b) found that a separation bubble would be developed more by the ground level than by the angle of attack. Ying, Yang, and Yang (Ying et al., 2010) demonstrated that the separation bubble disappears at a ground clearance value over 0.2, and the aerodynamic behaviour of the air flow on fixed ground was similar to moving ground.

Yang and Yang (2009) numerically investigated the effect of ground viscous effect in WIG effect. They found a negative lift coefficient and a rapid increase of drag coefficient with a small angle of attack (AOA $\leq$ 4°) at low ground clearance ($h/c \leq 0.1$). At an angle of attack of 4° and different ground clearance values, they reported a higher lift and lower drag for fixed ground compared to moving ground. However, this difference was reduced at higher ground clearance. An experimental study

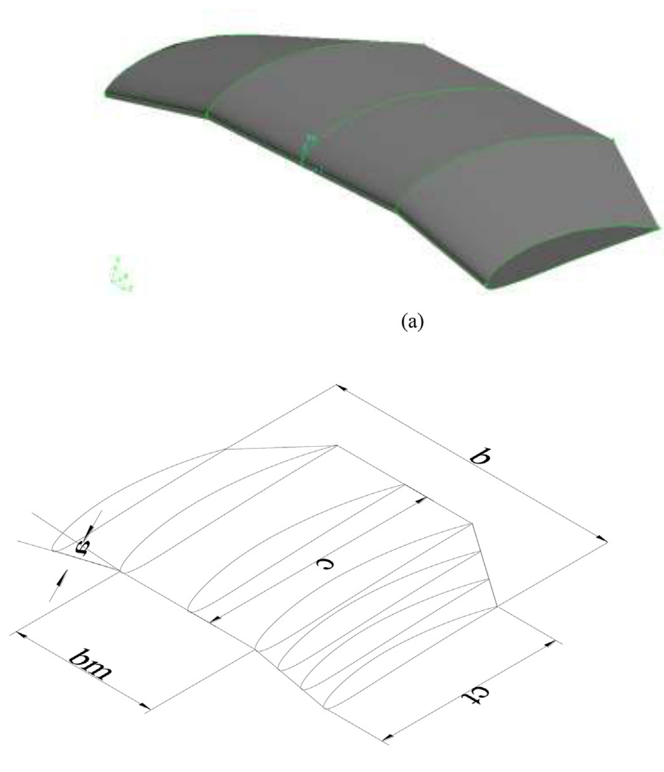

Fig. 1. (a) Compound wing, (b) Geometry of the compound wing.

was carried out on an airfoil section in a low turbulence wind tunnel with a moving ground model by Ahmed, Takasaki, and Kohama (Ahmed et al., 2007). They recorded the pressure distribution, velocity, and wake region of flow field over the airfoil surface, lift, and drag forces. A fall of suction on the upper surface was shown when the airfoil moved towards the ground for all angles of attack. The lift force dropped as the ground clearance decreased for a small angle of attack, but improved for greater angles of attack by enhancing the pressure distribution on the pressure surface.

Jamei et al., 2014a, 2014b numerically investigated the flow structure and aerodynamic coefficients of the compound WIG effect for