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Computational analysis of static height stability and aerodynamics of vehicles with a fuselage, wing and tail in ground effect

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A B S T R A C T

Wing-in-ground (WIG) effect vehicles skim the surface of the ground or water using an air cushion between the vehicle and the surface. The lift augmentation and drag reduction are considerable compared to an airplane flying out of ground effect and significantly enhance the aerodynamic performance. However, the stability problem is still a challenge for researchers and designers of WIG effect vehicles. In a previous study, sectional shapes were optimized for the wing-in-round effect (WIG) using computational fluid dynamics (CFD) and multi-objective optimization with two objectives: the aerodynamic center of height, which is part of the static height stability, and the lift-to-drag ratio. The optimization study obtained 113 optimal solutions called Pareto optima or Pareto sets, which include various airfoil profiles such as a flat lower surface and a convex lower surface next to the trailing edge. In this study, some of the Pareto optima that show the characteristics of features in the design domain are selected, and are applied to a three-dimensional vehicle with a fuselage, lifting and control surfaces such as a horizontal tail. Three featured optima that show high stability, high performance, and relatively stable cases are carefully investigated using computational methods to analyze the aerodynamic characteristics, stability, and three-dimensional effects.

1. Introduction

Wing-in-ground (WIG) effect vehicles skimming over water or ground surfaces use an air cushion between the vehicle and the surface. The speed of the oncoming air gradually decreases under the lower surface of the vehicle (pressure side) because of the small gap between wing and surface. The reduction of the dynamic pressure by the small gap tends to be associated with high static pressure under the vehicle including a wing, and this eventual increase in pressure is called the air cushion or the ram effect. The air with high dynamic pressure under the wing stagnates, and the pressure of the pressure side becomes extremely high. Therefore, the lift augmentation and drag reduction are considerable compared to an airplane operating out of ground effect, and they enhance the aerodynamic performance (the lift-to-drag ratio).

WIG vehicles are expected to have the high aerodynamic efficiency and reduced energy consumption. Early researchers observed these phenomena during takeoff and landing (Rozhdestvensky, 2006; Kikuchi et al., 1997; Joh and Kim, 2004; Kim and Joh, 2004). Some of the leading researchers applied this phenomenon to improve the vehicle performance actively. The extreme aerodynamic enhancement has attracted much attention until these days. Ships cannot match the speed of WIG vehicles, and they are more economical than other aircraft in terms of the operational expenses. Therefore, WIG vehicles could fill the niche between ships and aircrafts, and show great potential for a next-generation transportation.

Despite their attractive aerodynamic advantages, WIG vehicles have technical difficulties such as hump drag when taking off and instability in the ground effect. These issues are generally not observed in typical aircraft flying out of ground effect. Improving the stability and control, usually requires a huge vertical T-tail, an S-shaped wing profile, a tandem configuration, or a sophisticated control system (Rozhdestvensky, 2006). WIG vehicle industries are still limited by these technical difficulties. Until recently, experimental and numerical research on the ground effect has concentrated on the aerodynamic characteristics of the wing profile, three-dimensional configuration, fuselage, and tail configuration (including the area of the tail).

Joh et al. (Joh and Kim, 2004) numerically studied the pressure change, drag, and stability around the airfoils of WIG vehicles for two- and three-dimensional configurations. Decreasing the height of the vehicle to the ground causes of changes the velocity distribution around the airfoil. The motion of vehicles near the ground strongly affects the characteristics of the boundary layer. Ghadimi et al. (2012) investigated the boundary layers according to the vehicles height and Reynolds numbers. The boundary layer characteristics (such as the transition phenomena, separation location, and boundary layer thickness) and aerodynamic properties (such as lift and drag) were functions of the Reynolds number, angle of attack, flight height, and thickness of the airfoil. Approaching the ground surface results in a drop in local Reynolds number at the surface of the airfoil, which leads to a delay of the transition. An Increase in momentum thickness results in accelerated the flow separation, and the thickness of the boundary layer increases. The lift was shown to have no significant alteration, but the

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Nomenclature

C	Chord length
C_D	Drag coefficient
C_L	Lift coefficient
$C_{L,h}$	Derivative of lift coefficient due to height
$C_{L,\alpha}$	Derivative of lift coefficient due to angle of attack
C_M	Moment coefficient at trailing edge
$C_{M,h}$	Derivative of moment coefficient due to height
$C_{M,\alpha}$	Derivative of moment coefficient due to angle of attack
C_p	Pressure coefficient
h	Height at center of gravity
HS	Static height stability ($X_h - X_\alpha$)
k	Turbulent kinetic energy
p	Pressure
Re	Reynolds number
S_{ij}	Mean strain rates
u_i, u_j	Velocity component
x_i	Coordinate system
X_{ac}	Aerodynamic center
X_h	Aerodynamic center of height ($C_{M,h}/C_{L,h}$)
X_α	Aerodynamic center of pitch angle ($C_{M,\alpha}/C_{L,\alpha}$)
α	Angle of attack
ε	Turbulent dissipation rate
ρ	Density
μ_t	Turbulent viscosity

drag affected considerably and shows a tendency to increase.

Sun et al. (2007) performed an experimental study on the hydrodynamic interactions between a three-dimensional oval in ground effect with a numerical regression. The boundary hydrodynamic interactions of a model with a small aspect ratio was almost linearly dependent on the angle of attack, but there was only a small effect of the moving speed of the body on the hydrodynamic coefficients. The effect of clearance was related to the geometry, and the hydrodynamic forces between Re = $2.5 \times 10^5 \sim 1 \times 10^6$ were constant.

Qu, Wang, and Liu (Qu et al., 2015) investigated the aerodynamics, and flow characteristics of a NACA 4412 airfoil in ground effect for the wide range of heights, and angles of attack with numerical methods. They found that the aerodynamics characteristics could be divided into three different regions according to positive and negative ground effects. The region I showed the positive ground effect and the other two regions showed the negative ground effect. In region I, the airflow is blocked in the convergent passage between the pressure side and the ground, resulting in increases of pressure on the pressure side. In the region II with high angles of attack, the adverse pressure gradient increases, and results in a larger region of the flow separation. In region III with negative angles of attack, there are the large suction and the negative ground effect by the Venturi effect by the convergent-divergent passage between the surface and the ground.

The WIG vehicle experiences the wavy water surface instead of the flat that changes the aerodynamic characteristics (lift and moment). Qu et al. (2014) performed the numerical simulation employing the compressible Reynolds-averaged Navier-Stokes equations and the Spalart-Allmaras turbulent model. The simulation includes wings (side, endplate and central wing), fuselage, and tail. The lift, nose-down pitching moment and lift-to-drag ratio increase and decrease according to uphill climb and downhill of wavy water surface, respectively. However, the average of the aerodynamic coefficient of both wavy water surface and flat rigid surface are similar. At high angle of attack (AOA = 9 deg.), the reducing the height strengthens the span-wise flow on the upper flow of the central wing and the boundary layer at the central wing tip becomes thicker.

Dakhrabadi and Seif (2016) investigated the composed wings and their stability. The vehicle has an inner wing with a low aspect ratio, which is in ground effect and an outer wing with a high aspect ratio. The location of the outer wing with respect to the main wing influenced the static stability, and the characteristics of the static height stability which is very important for a safety of the WIG craft with composed wings. The main wing plays an important role in the aerodynamic coefficients of the compound WIG under an extreme ground effect, and its role decreases as the vehicle moves away from the ground. The outer wing can enhance the aerodynamic performance of the compound WIG at a higher flying height in ground effect. The static height stability criterion of the compound WIG was also discussed for the various outer wing positions. The results showed that the static stability of the compound WIG could be increased by shifting the outer wing to the trailing edge of the main wing.

Yang et al. (2015) derived stability conditions for a high lift device (hydrofoil) that included Irodov's height stability condition (Irodov, 1970). To improve the stability, the hydrodynamic center of heave should be located behind the aerodynamic center of height, aerodynamic center and center of gravity. They also concluded that a hydrofoil located behind center of gravity provides a sufficient pitch stability margin when taking off or in float. Turning in ground effect is different from that of out of ground effect, and so are the aerodynamic characteristics and vortex shedding at the wing tip. Jia et al. (Jai et al., 2016) performed a numerical analysis on three wing configurations: a rectangular wing with an endplate and one without an endplate, and a reverse delta wing. Numerical simulations were carried out to simulate the flow of a banked wing in ground effect.

Even though two-dimensional analyses are conducted for airfoil sections, vehicles do not fly in such conditions. The three-dimensional effects and configuration should be considered carefully. Recently, Lee and Lee (2013) performed a numerical optimization of airfoil shapes that were parameterized using Bezier curves. Due to the trade-offs between the multiple objectives, the optimal solutions are a set of wing profiles that are not dominated by the other designs within the given design space. The 113 non-dominated optimal solutions are known as the Pareto optima (or set), could be obtained. The Pareto optima include various shapes of the airfoil, and the aerodynamic characteristics of the Pareto optima were analyzed in detail.

The Pareto optima can be divided according to two significant features: a high lift-to-drag ratio and high stability based on the wing profiles. This study focused on the aerodynamic performance of a WIG vehicle with a three-dimensional wing, fuselage and tail. The wing section is based on the Pareto optimum obtained by Lee and Lee (2013). The wing section of the WIG vehicle is very important for the stability and aerodynamic performance. The ultimate goal for a WIG vehicle is to sustain high performance with sufficient safety under the ground effect. A computational analysis has been performed with the optimized wings applied to the WIG vehicle, and the aerodynamic performance has been analyzed. Based on this study, a three-dimensional optimization including wing and fuselage can be conducted to reduce the horizontal tail and improve the static stability in near future.

2. Numerical method

2.1. Governing equations and validation

The flow around the vehicle is assumed to be three-dimensional, turbulent, in steady state, and incompressible. The turbulent flow of the air is described by the Reynolds-averaged Navier-Stokes (RANS) equations, which can be expressed in tensor notation for the mass and momentum as follows: