Aerospace Science and Technology 55 (2016) 177–188

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

# Influence of main and outer wings on aerodynamic characteristics of compound wing-in-ground effect

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A R T I C L E I N F O

*Article history:*
Received 6 March 2016
Received in revised form 12 May 2016
Accepted 1 June 2016
Available online 3 June 2016

*Keywords:*
Aerodynamic characteristics
Static height stability
Compound WIG
Ground effect
Endplate

A B S T R A C T

A practical mathematical model with low computational time and good accuracy is applied to investigate the aerodynamic characteristics and static height stability of the compound wing-in-ground effect (WIG). The compound WIG consists of a main wing with low aspect ratio and an endplate, and an outer wing with high aspect ratio. To validate the present mathematical model, a numerical simulation is performed so that numerical results had a good agreement with the experimental data. The analysis shows that the main wing is useful in the extreme ground effect zone and the outer wing enhances performance of the compound WIG in the weak ground effect zone. In order to satisfy the static height stability of the compound WIG it is evaluated by Irodov's criterion. Influence of junction position of outer wing on the main wing is investigated on the static height stability of compound WIG. A comparison of Irodov's criterion shows that static height stability improves with moving the outer wing position backward into the trailing edge of the main wing and this led to a decrease in the tail area. The proposed mathematical model could be appropriate for aerodynamic optimization of WIG crafts with the compound wing.

## 1. Introduction

In recent years, the interest in fast transportation has been intensified. The development of tourism has increased the need for ferry operators, which in turn led to the discovery of new vehicle types with higher speeds and greater transport efficiencies.

The wing-in-ground (*WIG*) operates near the water or ground surface by using the air cushion of relatively highly pressurized air generated between the wing and the surface. The air cushion enhances lift and reduces drag considerably compared to a wing out-of-ground effect. Generally, the ground effect was used to increase the aerodynamic performance of high speed marine vehicles (e.g., racing boat). In the early 1960s, Russian researchers started to design and manufacture *WIG* crafts. Then other countries like Germany, USA, Australia, China, South Korea, Iran and Malaysia showed interest in the development of this technique in designing and upgrading high speed marine vehicles. Airplanes use wings with a high aspect ratio, whereas conventional *WIG* crafts use wings with low aspect ratio for enhancing aerodynamic performance. The aerodynamic characteristics of favorite *WIG* crafts could be improved by utilizing a compound wing (e.g., Swan and Ivolga [1]). Fink and Lastinger [2] conducted experimental investigations to evaluate aerodynamic characteristics of rectangular wing with low aspect ratio in close proximity of ground. They evaluated aerodynamic characteristics of wing with Glenn Martin 21 asymmetry airfoil section with aspect ratios of 1, 2, 4 and 6 in different ground clearances [2]. Chun and Chang [3] derived static and dynamic stability criteria for a 20-passenger *WIG* from motion equations and wind tunnel test data. Based on their study, one of the easiest ways in increasing the static stability is to increase the tail wing size at the cost of the heavier structural weight and increased drag [3]. Park and Lee [4] numerically calculated aerodynamic characteristics of a wing with Glenn Martin 21 airfoil section and aspect ratio of 1 in the ground effect with and without endplate. They found that the endplate prevented the high-pressure air from escaping out of the lower wing surface, reducing the influence of the wing-tip vortex [4]. Jung and Chun [5] also performed a series of wind-tunnel examinations to determine effects of endplate on the aerodynamic characteristics of wing with a NACA 6409 section near the ground. As a result of the ground effect and the influence of the endplate, aerodynamic performance increased at low ground clearance and the center of pressure moved forward to the leading edge [5]. Kim et al. [6] presented an aerodynamic optimization technique for configuration of a *WIG* craft by *VLM*, which can achieve the maximum lift and satisfy the static height stability within the design constraints. In addition, the optimization tool was evaluated optimal position of the side wing attached

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http://dx.doi.org/10.1016/j.ast.2016.06.002
1270-9638/© 2016 Published by Elsevier Masson SAS.

## Nomenclature

*Symbols*

| | | |
|---|---|---|
| *WIG* | Wing-in-ground effect | |
| *RANS* | Reynolds averaged Navier–Stokes | |
| *CFD* | Computational fluid dynamics | |
| *VLM* | Vortex lattice method | |
| *SST* | Shear stress transport | |
| $c$ | Chord of wing | m |
| $h$ | Height of flight at trailing edge | m |
| $h_e$ | Effective height of endplate | m |
| $h/c$ | Ground clearance | |
| $b$ | Wing span | m |
| $AR$ | Aspect ratio | |
| $AR_e$ | Equivalent aspect ratio | |
| $P$ | Pressure | $\mathrm{N/m^2}$ |
| $P_{relative}$ | Relative pressure | $\mathrm{N/m^2}$ |
| $F$ | Vertical force act on airfoil | N |
| $M$ | Moment of the airfoil | N m |
| $V_\infty$ | Free stream velocity | m/s |
| $u_\mathrm{i}$, $u_\mathrm{j}$ | Velocity component | m/s |
| $g$ | Gravity (9.81 $\mathrm{m/s^2}$) | |
| $C_L$ | Lift coefficient | |
| $C_D$ | Drag coefficient | |
| $C_M$ | Pitching moment coefficient | |
| $C_{L\infty}$ | Lift coefficient at free stream | |
| $C'_L$ | Lift coefficient due to ground effect | |
| $C_{D,f}$ | Friction drag coefficient | |
| $C_{D,p}$ | Pressure drag coefficient | |
| $C_{D,i}$ | Induced drag coefficient | |
| $C_{M\infty}$ | Pitching moment coefficient at free stream | |
| $C'_M$ | Pitching moment coefficient due to ground effect | |
| $G_k$ | Generation of $k$ due to the mean velocity gradients | |
| $G_\omega$ | Generation of $\omega$ due to the mean velocity gradients | |
| $Y_k$ | Dissipation of $k$ due to turbulent | |
| $Y_\omega$ | Dissipation of $\omega$ due to turbulent | |
| $D_\omega$ | Cross-diffusion term | |
| $S_k$ | User-defined source term for $k$ | |
| $S_\omega$ | User-defined source term for $\omega$ | |
| $y^+$ | Value of shear Reynolds number on the wing surface | |
| $R$ | Endplate influence ratio | |
| $H.S.$ | Height stability | |
| $x_\alpha$ | Aerodynamic center in pitch per chord length | |
| $x_z$ | Aerodynamic center in height per chord length | |
| $x_{C.G}$ | Gravity center per chord length from leading edge | |
| $\mu$ | Air viscosity | kg/m s |
| $\rho$ | Air density | $\mathrm{kg/m^3}$ |
| $k$ | Turbulent kinetic energy | |
| $\omega$ | Turbulent dissipation energy | |
| $\alpha$ | Angle of attack | deg |
| $\varepsilon$ | Span efficiency factor | |
| $\sigma$ | Induced drag ground effect influence ratio | |
| $\Phi$ | Influence coefficient | |
| $\Gamma_k$ | Effective diffusivity of $k$ | |
| $\Gamma_\omega$ | Effective diffusivity of $\omega$ | |

to the main wing of the *WIG* craft [6]. Jamei et al. [7] numerically evaluated the aerodynamic characteristics of compound *WIG*, and compared them with the rectangular wing, suggesting that the performance of the wing was improved noticeably by using the compound aerodynamic configuration. Jamei et al. [8] also numerically studied effect of the ground boundary layer on the aerodynamic behavior and the height static stability of a compound *WIG*. They showed that stability of the compound *WIG* was higher than a common rectangular wing and the height stability for both wings was reduced when ground clearance decreased [8]. Maali et al. [9] proposed a practical method for calculation of aerodynamic coefficients of a rectangular *WIG*. After calculating aerodynamic coefficients of wing using a theoretical method in the ground effect, they developed a semi-empirical method for hydro-aerodynamic performance evaluation of an aerodynamically alleviated marine vehicle (AAMV) in the take-off phase [9].

Many numerical and experimental studies have been performed to predict the aerodynamic characteristics of wing and the effect of endplate in ground effect. A few studies have, however, focused on analyzing the compound *WIG*. The purpose of this paper was to present a fast, economical and practical model for aerodynamic evaluation of the compound *WIG*. It was considered that the compound *WIG* has two parts: a main wing with an endplate, and an outer wing with aspect ratios of 1 and 4, respectively. Firstly, to validate the present mathematical model, a numerical simulation was carried out; the results of which had a good correlation with the experimental data. Then results of the mathematical model were compared to results of the proposed numerical simulation. It was shown that the results were in good agreement with the numerical results over a wide range of angles of attack. Then, influence of main and outer wings on the aerodynamic characteristics of the compound *WIG* was presented in the ground clearance at the trailing edge of main wing. The characteristics of the static height stability which is of prime importance in a safe compound *WIG* design, was also described with the influence of the outer wing position respect to the main wing on the stability of the compound *WIG*. Often, the outer wing with a dihedral angle is applicable for improving the roll stability when the compound *WIG* is out-of-ground effect. But target of this study is not the evaluation of roll stability.

## 2. Numerical approach

### 2.1. Governing equations and boundary conditions

In the realm of the ground effect, most of numerical simulations by previous researchers have been focused on steady flow around airfoils [10–12], wings with endplate [4,13,14] and the *WIG* crafts [6,15]. As mentioned above, Jamei et al. investigated the aerodynamic characteristics of a compound *WIG*, but their proposed compound *WIG* was composed of three parts with one rectangular wing in the middle and two forward-swept wings with anhedral angle at the side. Therefore their aerodynamic configuration was different from the compound *WIG* used in this study. In this section, three-dimensional simulation was performed to investigate the aerodynamic characteristics of the compound *WIG* with Glenn Martin 21 airfoil section. The compound *WIG* contains two parts: a main wing with endplate and an outer wing (Fig. 1). The main wing with endplate was an internal part of the compound wing with low aspect ratio (approximately square) that employs the high-pressure ram effect to improve lift in the extreme ground effect. The outer wing is an external part of the compound wing with high aspect ratio that is similar to an infinite wing with good aerodynamic performance at out-of-ground effect. The airflow around the compound *WIG* was assumed to be steady-state, incompressible and turbulent.

The present numerical simulation was carried out by ANSYS CFX 15, which fluid flow around the compound *WIG* was simulated