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Numerical study of aerodynamic forces and flow physics of a delta wing in dynamic ground effect

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A B S T R A C T

During takeoff and landing processes, the aerodynamic characteristics of a delta wing configuration aircraft are influenced by the dynamic ground effect (DGE). In this paper, the DGE during the landing process of a 65° sweep delta wing (VFE-2) with sharp leading edge is numerically studied at AOA $= 23°$. The unsteady compressible Reynolds-Averaged Navier–Stokes equations and Spalart–Allmaras turbulence model are discretized using the finite volume method. With the ride height decreasing, the lift, drag and nose-down pitching moment increase nonlinearly, and the increments become larger with the sink velocity increasing. The DGE can be divided into three regions based on the aerodynamics and flow physics. In the large ride height region, the aerodynamic forces in DGE remain unchanged with the ride height decreasing, and they are equal to those in static ground effect (SGE) as long as the angles of attack (AOAs) are equal; the ground effect (GE) can be neglected. In the medium ride height region, the aerodynamic forces in DGE increase slowly with the ride height decreasing, and they are still equal to those in SGE as long as the AOAs are equal; SGE governs the flow. In the small ride height region, the aerodynamic forces in DGE increase significantly with the ride height decreasing, and they are much larger than those in SGE although the AOAs are equal; SGE and compression work effect govern the flow together. Among them, SGE stagnates the airflow under the delta wing, increasing the pressure on the windward surface; simultaneously, it enhances the primary vortex strength, promotes its breakdown and drives it outward along the span. The compression work effect further increases the pressure on the windward surface; however, it has little influence on the airflow over the delta wing.

1. Introduction

When an aircraft flies in the proximity to the ground, its flow structures and aerodynamic forces may significantly differ from those in the unbounded flow [1]. In the realm of ground effect (GE) aerodynamics, previous studies mainly focused on the steady flow around airfoils [1], wings [2] and aircrafts [3] at fixed ride heights above the ground, which is called static ground effect (SGE). However, the flight height changes continuously during take-off and landing, which is called dynamic ground effect (DGE); considering these two phases are the most dangerous phases in the whole flight envelope, it's of more practical significance to study the aerodynamic characteristics of aircrafts in DGE than in SGE.

Now, the delta wing has been widely implemented on modern fighters and unmanned combat aerial vehicles. These aircrafts often need the emergent landing, during which the angle of attack (AOA) and sink velocity are much larger than those in the conventional landing process. Therefore, the study of a delta wing configuration in DGE at higher AOAs and sink velocities is of considerable interest to ensure the flight safety [4].

In fact, GE can be classified into the attached flow GE of high-aspect ratio wings for transport aircrafts and the separated flow GE of delta wings for fighters based on the flow physics. The former can be further classified into the chord dominated GE and the span dominated GE [4,5]. Among them, the chord and span dominated SGEs have been widely studied and recognized, while the chord and span dominated DGEs only receive a few studies and remain not well understood. As for the delta wing to be studied in the present paper, previous studies mainly focused on the variations of aerodynamic forces in both SGE and DGE, leaving the flow physics behind the aerodynamics still unknown. In the following context, a comprehensive study of DGE will be reviewed.

The studies on the chord dominated DGE include the take-off/landing process and the heaving process of an airfoil. Chen and Schweikhard [6] and Nuhait and Zedan [7] studied the landing process of a 2D flat plate using the vortex-lattice method (VLM). In their studies, Chen and Schweikhard assigned the wake along

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Nomenclature

b	wing span
C	chord length of the 2D airfoil
CR	root chord length of the delta wing
CRa	reference length in wind coordinate system, $CR\cos\alpha$
CR	reference length in vortex coordinate system, CR
C_P	pressure coefficient
C_L	lift coefficient
C_D	drag coefficient
C_M	pitching moment coefficient about the quarter-chord point
C_X	a universal aerodynamic coefficient
Cp_d	dynamic pressure coefficient
$\overline{Cp_d}$	volume averaged dynamic pressure coefficient
Cp_s	static pressure coefficient
$\overline{Cp_s}$	volume averaged static pressure coefficient
Cp_t	total pressure coefficient
$\overline{Cp_t}$	volume averaged total pressure coefficient
H	ride height, i.e. the distance from the trailing edge of the delta wing (or the airfoil) to the ground
H_0	initial ride height, i.e. the H where the simulation starts
$\boldsymbol{j}$	unit vector along lift direction
Ma	Mach number
$\boldsymbol{n}$	unit vector normal to the delta wing surface
$OXYZ$	body coordinate system
$OXaYaZa$	wind coordinate system
$OXoYoZo$	vortex coordinate system
P_d	dynamic pressure
P_s	static pressure
P_t	total pressure
P_∞	free stream static pressure
Q	positive second invariant of the velocity gradient tensor
$Q_{\max}$	maximum Q value close to the vortex center in the local cross section
Re	Reynolds number based on the airfoil chord
Re_{mac}	Reynolds number based on the mean aerodynamic chord
$Rossby$	ratio of the local maximum axial velocity to the local maximum circumferential velocity
S	surface area of the Delta wing
s^*	local semi-span
t	thickness of the delta wing
U_∞	free stream velocity, $=\sqrt{U_H^2+U_V^2}$
U_H	horizontal component of the free stream velocity
U_V	wing sink velocity, i.e. vertical component of the free stream velocity
V	the defined control volume under the model
V_{Ya}	span wise velocity component along the OYa axis in wind coordinate system
Vza	vertical velocity component along the OZa axis in wind coordinate system
$y+$	dimensionless wall distance of the first mesh layer
α	angle of attack (AOA)
γ	flight path angle
θ	pitch angle
λ	sweep angle
ρ	air density
σ	magnitude of the local flow velocity
φ	angle between the tangent vector of streamlines and the horizontal
$\boldsymbol{\tau}$	shear stress on the delta wing surface
Δt	time step
ΔC	the increment of an aerodynamic force coefficient
$\varGamma$	strength of the primary vortex core
$\varOmega Xa$	vorticity component along the OXa axis in wind coordinate system

Subscripts

Wi	Windward surface of the delta wing
Le	Leeward surface of the delta wing

Superscripts

H	in ground effect with the ride height of H
∞	out of ground effect

the flight path, while Nuhait and Zedan allowed the wake to deform freely. Both studies showed that the lift in DGE is larger than that in SGE, and the difference becomes larger with the sink velocity increasing. To get more flow information and explain the variation of aerodynamic forces mentioned above, Qu et al. [4] simulated the landing process of a NACA 4412 airfoil with the finite volume method. The flow information including pressure, velocity and streamlines were presented in detail, and the compression work effect was introduced to explain why the lift in DGE is larger than that in SGE. Matsuzaki et al. [8] conducted a wind tunnel experiment of the NACA 6412M airfoil moving down/up near the fixed ground plane in the incoming flow, the results showed that the lift in the down/up process is smaller/larger than that in the steady cases, which is contrary to the results of Refs. [4,6,7]. Matsuzaki et al. adopted the up-wash or down-wash effect induced by the shedding wake to explain the aerodynamic characteristics during the heaving process, but no flow information was measured to support their explanation. It was suggested by Qu et al. [4] that the different results in Ref. [8] were due to the fixed ground plane adopted in the wind tunnel experiment. Moryossef and Levy [9] and Molina and Zhang [10] also numerically simulated the flow of an inverted airfoil in a heaving motion near the ground. The ground effect, incidence effect and added mass effect were introduced to analyze the lift lag, and the viscous effect was checked in detail. Considering all the studies mentioned above, only Ref. [4] provided the limited flow information in a landing process. Therefore, more flow information is needed to analyze the aerodynamic forces and flow physics in the chord dominated DGE.

For the span dominated DGE, Nuhait and Mook [11] extended the VLM used in Ref. [7] to simulate the landing process of the 3D rectangular wings. Results showed that the lift in DGE is larger than that in SGE, and the difference becomes larger with the sink velocity increasing; increasing the aspect ratio will increase both the SGE and DGE. Ariyur [12] studied the take-off and landing processes of an elliptical wing through modified lifting line theory. It was found that the lift decreases with the descent angle increasing and increases with the ascent angle increasing, which is contrary to the conclusion from Nuhait and Mook [11]. It's clear that the span dominated DGE is more complicated than the chord dominated DGE due to the 3D effect, and the aerodynamic forces and flow physics in the span dominated DGE are still far from being understood.

As for the DGE of delta wings, previous studies mainly adopted flight tests and wind tunnel experiments to measure the aerodynamic forces. Besides, there are a few numerical studies.