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Numerical simulation of flow over an airfoil in heavy rain via a two-way coupled Eulerian–Lagrangian approach

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ABSTRACT

Airfoil performance degradation in heavy rain has attracted many aeronautical researchers' eyes. In this work, a two-way momentum coupled Eulerian–Lagrangian approach is developed to study the aerodynamic performance of a NACA 0012 airfoil in heavy rain environment. Scaling laws are implemented for raindrop particles. A random walk dispersion approach is adopted to simulate raindrop dispersion due to turbulence in the airflow. Raindrop impacts, splashback and formed water film are modeled with the use of a thin liquid film model. The steady-state incompressible air flow field and the raindrop trajectory are calculated alternately through a curvilinear body-fitted grid surrounding the airfoil by incorporating an interphase momentum coupling term. Our simulation results of aerodynamic force coefficients agree well with the experimental results and show significant aerodynamic penalties at low angles of attack for the airfoil in heavy rain. An about 3° rain-induced increase in stall angle of attack is predicted. The loss of boundary momentum by raindrop splashback and the effective roughening of the airfoil surface due to an uneven water film are testified to account for the degradation of airfoil aerodynamic efficiency in heavy rain environment.

Introduction

Aerodynamic penalty of aircraft flying in heavy rain has been considered as a major cause of many severe aviation accidents in rain conditions (Luers and Haines, 1981, 1983; Cao et al., 2014). A rainfall at the rate of 1800 mm/h can cause a 30% decrease in lift and a 20% increase in drag and can also affect the stall angle of attack, boundary-layer separation, flight safety and maneuverability (Haines and Luers, 1982). Meteorologists and aeronautical communities have paid much attention to rain associated with thunder storms for a long time.

Investigation of rain effects on aircraft aerodynamics was begun with wind-tunnel testing, and perhaps the earliest investigation was conducted by Rhode (1941). His analysis showed that the drag increase associated with the momentum imparting a DC-3 aircraft encountering a rain cloud of liquid water content (LWC, which is a common term in the rain research to denote intensity of rainfall and is usually in unit of g/m^3) of $50\,g/m^3$ would induce an 18% reduction in airspeed. Haines and Luers (1982) did a research concerning the frequency and intensity of very heavy rainfalls as well as their adverse effects on a landing aircraft. Their work demonstrated that heavy rain can cause not only decreases in the maximum lift but also increases in the roughness of wing surface. Hansman and Craig (1987) compared the changes in the low-Reynolds-number aerodynamic performance of the NACA 64-210, NACA 0012 and Wortman FX 67-K170 airfoils in the wind-tunnel simulated heavy rain condition and explored the various underlying mechanisms of the rainfall effects by forcing boundary layer to transition. In other analogous wind-tunnel experiments, laminar-flow airfoils were also found to experience performance degradations which are approximately equivalent to that caused by tripping boundary layer to turbulence (Campbell and Bezos, 1989; Yip, 1985; Hansman and Barsotti, 1985). Bezos et al. (1992) studied the severity of rain effect, the aerodynamic penalty over a range of rainfall intensities and the importance of surface tension interactions of water as a scaling parameter. Thompson et al. (1995) examined the aerodynamic performance of the NACA 4412 airfoil in a wind-tunnel simulated rain environment. They also studied the correlation between the surface-film behavior and the aerodynamic efficiency for the same airfoil in a moderate rain condition (Thompson and Jang, 1996). Comparisons with different flow patterns showed that the aerodynamic performance degradation depended on the location of rivulet formation and the diameter of these rivulets.

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Numerical simulation was introduced and developed greatly with the development of computer science and technology in the last twenty years. Valentine and Decker (1995a,b) developed both one-way and two-way momentum coupled Eulerian–Lagrangian approaches to study the aerodynamic performance of NACA 64-210 airfoil. The splashback of raindrop in the flow over the airfoil was successfully simulated, but the effect of water film formed on the airfoil surface was not involved. The location of the onset of rivulet formation in the surface-water flow over a wing with the NACA 4412 airfoil was calculated and compared to that by wind-tunnel experiment (Thompson and Marrochello, 1999). In the numerical simulation of heavy rain effect on airfoil performance conducted by Wan and Wu (2009), the water film layer and the vertical rain mass flow rate on the airfoil upper surface were added, thus increasing the roughening effects. The aerodynamic efficiencies of the NACA 64-210 cruise and high-lift configuration airfoils (Wan and Pan, 2010; Wan and Chou, 2012) and a 3-D Blended-Wing-Body aircraft (Wan and Song, 2012) under severe rain conditions were also studied. Ismail et al. (2014) and Wu et al. (2013) focused their study on the effects of rain on the aerodynamic efficiency of the NACA 0012 and NACA 64-210 airfoils and NACA 0012 wing by using two phase flow approaches. They simulated the aerodynamic efficiency degradations of both airfoils and wings in rain, and their simulation results agree with experimental values.

Two physical phenomena have been hypothesized to contribute to the degradation of airfoil performance in rain. As raindrops strike an airfoil, some fraction of the incident mass is splashed back and forms an ejecta fog near the leading edge, while the remainder forms a thin water film upon the airfoil surface (Bezos et al., 1992), as shown in Fig. 1. The acceleration of the splashed-back droplets by the air is hypothesized to act as a momentum sink to the airfoil, decelerating the boundary-layer air flowfield (Valentine and Decker, 1995a,b). As subsequent raindrops impact the water film, many craters are formed and make the film uneven. The uneven water film can effectively roughen the airfoil surface, resulting in reductions of lift and increases in drag (Haines and Luers, 1982). In order to analyze the above two phenomena, a new numerical approach is proposed in this paper. Such work is important and significant for aviation safety since aircraft may be subjected to serious accidents when inevitably encountering a very heavy rainfall.

In numerical simulation, two approaches have been used to model multiphase flows, i.e. the Eulerian–Eulerian model and the Eulerian–Lagrangian model. The Eulerian–Eulerian model treats both the continuous fluid phase and the dispersed particle phase as a continuum and conservation equations are solved for each phase. Interphase exchanges of mass, momentum and energy are included as source terms in the appropriate conservation equations. This model is suitable for particles of a uniform size. The Eulerian–Lagrangian model solves the time-averaged Navier–Stokes equations for the continuous fluid phase first and then integrates Lagrangian motion equations to track the dispersed particle, which is also called Discrete Phase Model (DPM). There are two models including a one-way coupled model and a two-way coupled model in the Eulerian–Lagrangian approach. The one-way coupled model assumes that particle motion is affected by the continuous phase but the continuous phase is not affected by the dispersed particle phase. The two-way coupled model considers the two-way exchanges of mass, momentum and energy between the two phases. In addition, two approaches have been applied in the Eulerian–Lagrangian two-way coupled model. One is a non-iterative transient scheme where the evolutions of the fluid and particle flow fields are taken into consideration simultaneously (Dukowicz, 1980). The other is an iterative particle source in cell (PSI-Cell) method (Crowe et al., 1977) in which the two fields are considered separately and updated iteratively until a steady state is reached.

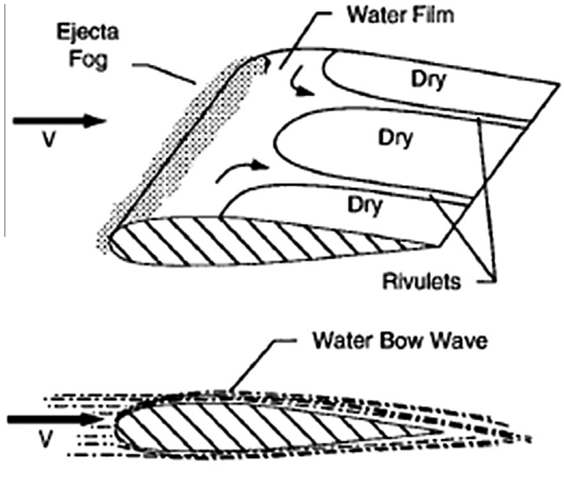

Fig. 1. Rain impacts on airfoil forming the droplet ejecta fog and surface water film (Bezos et al., 1992).

It is assumed that the rain droplets in the current study are non-evaporating, non-interacting and non-deforming spheres. The assumption of non-interacting droplets has been justified by Bilanin (1987). According to his study, even for a high rainfall of 1872 mm/h and for an average raindrop diameter of 4 mm, the mean distance between raindrops will be of the order of 70 mm or 17.5 times the droplet diameter. Hence, raindrop collisions do not occur necessarily. He also investigated the evaporation of the particles near the surface and found that evaporation does not significantly affect the aerodynamic efficiency of the airfoil. The last assumption is to simplify our analysis, though actually raindrops are deformed as they enter the airfoil boundary layer.

In this work, a two-way momentum coupled Eulerian–Lagrangian approach is developed to study the flow around a NACA 0012 airfoil in a simulated heavy rain environment. The aerodynamic performance degradation of the airfoil due to heavy rain is particularly focused on. Then, the underlying physics in the aforementioned two phenomena that account for the aerodynamic degradation are revealed and discussed in detail. Our study may be found useful for the aviation community to better recognize the detrimental effects of heavy rain on aircraft aerodynamics and deepen the understanding of the underlying physical mechanisms in the aspect of the broader problem of aerodynamic performance degradation caused by heavy rain.

Methodology description

Continuous phase

The steady-state incompressible Reynolds-averaged Navier–Stokes equations of mass, momentum and energy are solved for the air flow field. The pressure-based segregated SIMPLE algorithm is adopted for pressure-correlation equation calculation, which is also used by the authors for simulating parachute aerodynamics (Cao et al., 2012). For spatial discretization, the pressure term uses second order scheme, the momentum, energy and turbulence terms use the second-order accurate QUICK scheme (Leonard and Mokhtari, 1990), which is based on a weighted average of the second-order central and upwind interpolations of the discretized variable. The k–ε turbulence model is added to model the turbulence effect. The governing equations are written as follows: