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Effects of rainfall on aircraft aerodynamics

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ABSTRACT

Rainfall has been considered as an important meteorological factor to threat aircraft flight safety. Adverse effects of rainfall on aircraft aerodynamics have been a constantly hot subject in meteorological aviation community for decades. This paper presents a systematic and comprehensive overview of the effects of rainfall on aircraft aerodynamics. The overview includes an introduction of rain-induced aviation accidents, a list of the hazards of rainfall to aircraft, the natural characteristics of rain, the existing rain research techniques, some aerodynamic considerations for rainfall simulation and the current state-of-the-art research achievements in the field of effects of rainfall on aircraft aerodynamics. Raindrop impingement, splashback and flow of the formed water film upon lifting surfaces effectively degrade aircraft aerodynamic performance, leading to severe aviation accidents. The previous lessons learned should be disseminated and accepted by later generations to avoid aviation accidents due to flight in heavy rain.

Contents

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1. Introduction

As the function of aircraft is expanding, aircraft has also been widely applied in various domains such as aerobatic flight, exploration, rescue, private flight, etc., in addition to the primary commercial and military functions. So it is required that aircraft fly normally in all kinds of weather conditions to accomplish the anticipated assignments. Although some measures like hourly sequence reports, terminal forecasts, low level windshear alert system (LLWAS), etc. are taken to avoid hazardous weather as much as possible [1–3], however, the fact is that since manned aircraft comes into being, flight accidents due to flying in adverse weather conditions like low-altitude wind shear, thunderstorm, atmospheric turbulence, frost, hail, lightning, ice accretion and rainfall have been reported year after year. Over 50% of commercial airline accidents are weather-related [4] and weather remains the greatest uncertain factor in flight operations, especially inclement weather which can bring numerous problems in aviation operations [5–9], thus deeply attracting people's attention to deal with it [10–16]. Over the aforementioned severe weather conditions, rainfall is of particular interest ever since and rain-induced aviation accidents are reported all over the world. In 1977, the America Federal Aviation Administration (FAA) conducted a survey of 25 aviation accidents and incidents occurring from 1964 to 1976, in which low-altitude wind shear was considered a contributing factor [17]. Of the 25 cases (23 were landing and 2 were take-off) in the survey, ten cases occurred in a rainy condition and five were identified as intense or heavy rain encounters. Rudich's statistical analysis of all accidents of all American airline companies from 1962 to 1984 suggested that in all the weather factors affecting flight safety, rainfall took up the proportion of 40%, exceeding wind shear and atmospheric turbulence and ranking the first [18]. The Eastern Flight 066 accident at Kennedy Airport (National Transportation Safety Board, NTSB, 1976) [19], the Flight 693 accident at Atlanta International Airport (1979) [20], the Flight 759 accident at New Orleans International Airport (1982) [21], the Korean Airlines Boeing 747 and the Vietnamese Tupolev accidents (1997) [22], the Far Eastern Air Flight 066 accident in Taiwan (2006) [23] and the MI-171 helicopter accident during the strong earthquake in Wenchuan County of Southwest China's Sichuan Province (2008) [24] are more or less due to adverse weather environment of rain associated with wind shears or thunderstorm. These results led to the consideration of rainfall as a potential weather-related aircraft safety hazard, particularly in the take-off and/or approach phases of flight. Even nowadays, people are still unable to resolve the threat of heavy rain to flight, the best means is to stop flying in heavily rainy days which is heard by the author from some airlines.

Although there have been many reviews about other adverse weather conditions, ice accretion in particular, only several short review articles involve the effects of rainfall on aviation in the 1980s and 1990s of the last century. Besides, with the computer technology advancing fast over the last 20 years, a new research approach for rain named Computational Fluid Dynamics (CFD) numerical simulation is emerging and has obtained new phenomena that traditional techniques like wind-tunnel experiment did not observe. This paper presents an overview of the effects of rainfall on aircraft aerodynamics. This overview includes the hazards of rainfall to aircraft flight safety, results of existing attempts to measure the natural characteristics of rain, a review of the current state-of-the-art methods for evaluating rainfall effects, some important scaling considerations for extrapolating model data as well as the latest research achievements on this subject. A complete understanding of the effects of rain on aircraft performance will require additional significant effort in both experimental and analytical ways before an assessment of the degree of hazard associated with flight operations in a rain environment can be made.

2. Hazards of rainfall to aircraft

Detrimental effects of rain on aircraft flight were firstly reported by Rhode in 1941 [25]. It suggested that rainfall could impart severe aerodynamic penalties to aircraft, but these penalties did not threat aircraft flight safety. It was not until Luers and Hanies conducted an assessment on the effects of heavy rain for a couple of flight accidents related to wind shear in 1981 that people in aviation community began to realize the seriousness of heavy rain endangering aircraft flight [26].

When an aircraft flies in a rain condition, particularly during the stages of takeoff and landing, its flight safety is threatened by massive detrimental effects of rain. The literatures [19,20,27–36] comprehensively discussed the main detrimental influences of rain on aviation, here we present a summary of them, which mainly include the following several aspects:

- Rain-induced visibility reduction is certainly a well-known phenomenon [37]. Rain can decrease visibility at least in the following two ways. In one way through the scattering of light from a large number of liquid droplets, high rainfall rates can reduce the visibility to less than 400 m. In the other way through the water film and splashing of raindrops on the windshield of an aircraft, high-speed windshield wipers will possibly deteriorate or even lose their effectiveness when encountering a heavy rain.
- Rain can affect the accuracy of measurement instruments on an aircraft. For example, it is important for an aircraft stall warning system to function well. An α-vane instrument is usually equipped to measure aircraft angle of attack to warn of impending stall. Because the direction of incoming raindrops that impact the α-vane can be up to 8° or 10° higher than that of the freestream air due to the vertical velocity of rain, the angle of attack of the vane will be influenced by the raindrops to some extent (as shown in Fig. 1). The bias will lead to a decrease in measured angle of attack, which will delay the warning of stall angle and inhibit the activation of the stall warning stick shaker. From literature [27] it is learnt that rain may also affect the accuracy of the pitot tube which measures the airspeed of an aircraft. It is just a speculation, however, since there has not appeared to be any strong evidence indicating that airspeed indicators do not work well in a heavy rain environment. Rain can also influence the accuracy of radar scatterometer measurements on the aircraft [35,38]. The wind sensitivity of the radar backscatter is known to rely on the resonance with the capillary waves of wavelength of 1.7 cm [39]. Raindrops can produce waves of a similar or larger size and disrupt the patterns of the wind-driven waves. Correlative calculations of wind vector from the SeaSat Active Scatterometer System (SASS) and related sensors suggest that measurements can still work well at high