Progress in Aerospace Sciences xxx (2017) 1–10

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

A review of recent wake vortex research for increasing airport capacity

James N. Hallock [a], Frank Holzäpfel [b,*]

[a] Retired, Waltham, MA, USA
[b] Institute of Atmospheric Physics, German Aerospace Center (DLR) Oberpfaffenhofen, D-82234, Wessling, Germany

ARTICLE INFO

Keywords:
Aircraft wake vortices
Wake behaviour
Meteorological effects
Wake decay
Lidar
Computational fluid dynamics

ABSTRACT

This paper is a brief review of recent wake vortex research as it affects the operational problem of spacing aircraft to increase airport capacity and throughput. The paper addresses the questions of what do we know about wake vortices and what don't we know about wake vortices. The introduction of Heavy jets in the late 1960s stimulated the study of wake vortices for safety reasons and the use of pulsed lidars and the maturity of computational fluid dynamics in the last three decades have led to extensive data collection and analyses which are now resulting in the development and implementation of systems to safely decrease separations in the terminal environment. Although much has been learned about wake vortices and their behavior, there is still more to be learned about the phenomena of aircraft wake vortices.

1. Introduction

In January 1991, one of us (JNH) published a report [1] that proposed alternative strategies for the US wake vortex program based on the then current knowledge of wake vortices. The expansion of the US program and the addition of many international wake vortex programs inspired the preparation of this updated review of the situation. This paper used the 1991 report as a starting point; the material herein is an update bringing the reader to 2018 by addressing the questions:

1. What do we know about wake vortices?
2. What don't we know about wake vortices?

within the context of increasing airport capacity. Two major additions to the state of knowledge of aircraft wake vortices in the last three decades are the introduction of the pulsed lidar as a data collection device and the use of computational fluid dynamics (CFD) in describing the behavior of wake vortices. The emphasis of this paper will be the results of analyses of both experimental data and numerical simulations. However, extra effort was expended in this paper to address the historical development of CFD; such an overview has not been given before and the historical context helps to better understand the limitations and benefits of CFD. A measure of the current state of knowledge is the introduction of systems at airports to mitigate the conservative fixed separations between aircraft in the terminal environment (RECAT in the US and RECAT-EU in Europe).

Pulsed lidar can track vortices at altitudes up to 1500 feet (457 m) and for long translational distances. The lidar processing algorithm identifies the two vortex centers and the velocity distributions and, by matching the velocity distributions to a model, yields the vortex strengths or circulations. Pulsed lidars have been used to monitor vortex behavior at various airports and locations along the final approach path and the initial takeoff path.

CFD has become a mature tool supporting the consistent investigation of wake vortex behavior under various environmental conditions and in ground proximity and even specific phenomena like the formation of double rings or vortex bursting have become tangible. However, CFD has not yet had a significant impact on aircraft spacing for airport capacity enhancement. This leads to the question what will be required to give safety regulators more confidence in CFD for safety purposes. The advantage of CFD is that almost all variables of interest are readily available for analysis. Although benchmarks between different simulation codes feature satisfactory agreement for various scenarios, substantial differences for vortex behavior in, for example, turbulent environments remain depending on the characteristics of the adopted turbulence. First examples of consistent consideration of the aircraft type, configuration and flight phase are emerging but need further development and validation to become a means for reliable assessments of specific scenarios.

The wake vortex problem is complex because of the large number of variables. Setting aside the various operational scenarios, the problem involves the parameters introduced by the vortex-generating aircraft, by

* Corresponding author.
E-mail address: frank.holzaepfel@dlr.de (F. Holzäpfel).

https://doi.org/10.1016/j.paerosci.2018.03.003
Received 13 December 2017; Received in revised form 12 March 2018; Accepted 13 March 2018
Available online xxxx

Please cite this article in press as: J.N. Hallock, F. Holzäpfel, A review of recent wake vortex research for increasing airport capacity, Progress in Aerospace Sciences (2017), https://doi.org/10.1016/j.paerosci.2018.03.003

the vortex-encountering aircraft and by the intervening atmosphere. The vortex is initially characterized by the parameters of the vortex-generating aircraft (weight, wingspan, speed, flap and spoiler settings, proximity to the ground, engine thrust, lift distribution, etc.). The encounter (safe or hazardous) is characterized by the parameters of the following aircraft (speed, wingspan, roll control authority, phase of flight, etc.). The meteorology (wind with its components headwind and crosswind, wind shear, atmospheric stability, turbulence, etc.) plays a leading role in determining how long a vortex remains hazardous.

Many surveys and reviews on wake vortex research have been published over the years. In 1975 the Annual Review by Widnall [2] and the extensive monograph of Donaldson and Bilanin [3] appeared, the latter still being a repository for analytical wake vortex methods. Hallock and Eberle [4] edited a state-of-the-art review of the US wake vortex R&D program as input for the ICAO ninth Air Navigation Conference held in 1977 to address wake vortex effects and separation standards. Twenty-one years later, Hallock et al. [5] provided a retrospection on mainly the US wake vortex activities and Spalart [6] presented his discerning and sobering review on the understanding of wake vortex physics as relevant to safety and productivity of aviation. One year later in 1999, Rossow [7] gave a historical review with a focus on wake structure and alleviation. In the year 2002, Gerz et al. [8] presented a consolidated European view on the status of knowledge on aircraft wake characteristics, technical and operational procedures of minimizing and predicting vortex strength, and avoiding wake encounters. Further research needs reports compiled within WakeNet-Europe networks appeared in the following years [9,10]. Breitsamter [11] gave a brief overview on past and present wake vortex research, followed by detailed reports on wind tunnel investigations including turbulence and instability characteristics.

2. Current knowledge of vortex behavior

Any finite lifting wing must leave behind it two counter-rotating trailing vortices, the direction of rotation being such that between these vortices the air moves downwards while outside of them the induced flow is upwards. The wake vortex originates in the vorticity shed from the generating wing (see Fig. 1). The vorticity can be resolved into streamwise (oriented with the flight direction) and cross-stream (aligned perpendicular to the flight path). If the wing contains significant regions of concentrated streamwise or cross-stream perturbations (due to control surfaces, flaps, spoilers, landing gear, etc.), there may be more than one vortex pair, and various stages may develop with different time scales compared to the clean-wing case. The various vortices interact and eventually combine into a single pair. The different stages may be delayed or accelerated; this situation occurs for aircraft in the landing or takeoff configurations.

Aerodynamics dominates the rollup process, but the ambient atmosphere eventually dictates how the vortices behave. Vortex motion and decay are stochastic processes; i.e., the vagaries of the atmosphere and slight changes in aircraft characteristics can lead to different vortex behavior even though it seems that all the conditions are the same. Stochastic processes require extensive data collection to determine the envelope of behavior.

2.1. Motion near the ground

The primary mechanism of vortex transport is mutual induction, that is, vortex motion is caused by each vortex being in the velocity field of the other vortex. Ground effect is calculated using image vortices, which are imaginary vortices whose presence creates the same effect as the ground plane, thereby obviating the need to otherwise model the ground plane. In the absence of wind shear, the vortices are of equal strength and descend together. It has been observed that vortices tend to descend to an altitude of about one-half of their initial separation (see Fig. 2). In inviscid flow and without crosswind, the vortex trajectory is a hyperbola. However, the upwind vortex can be expected to stall over the runway if the crosswind is approximately equal to the initial descent speed.

Extensive measurements indicate that the vortex pair upon reaching the point of closest approach to the ground will then rise in altitude. This is known as rebound and comes about due to the generation of a weak secondary pair of vortices outside and below the vortex pair as it nears the ground. The separation of the two vortices in ground effect leads to the familiar situation where a crosswind equal to half the speed of the

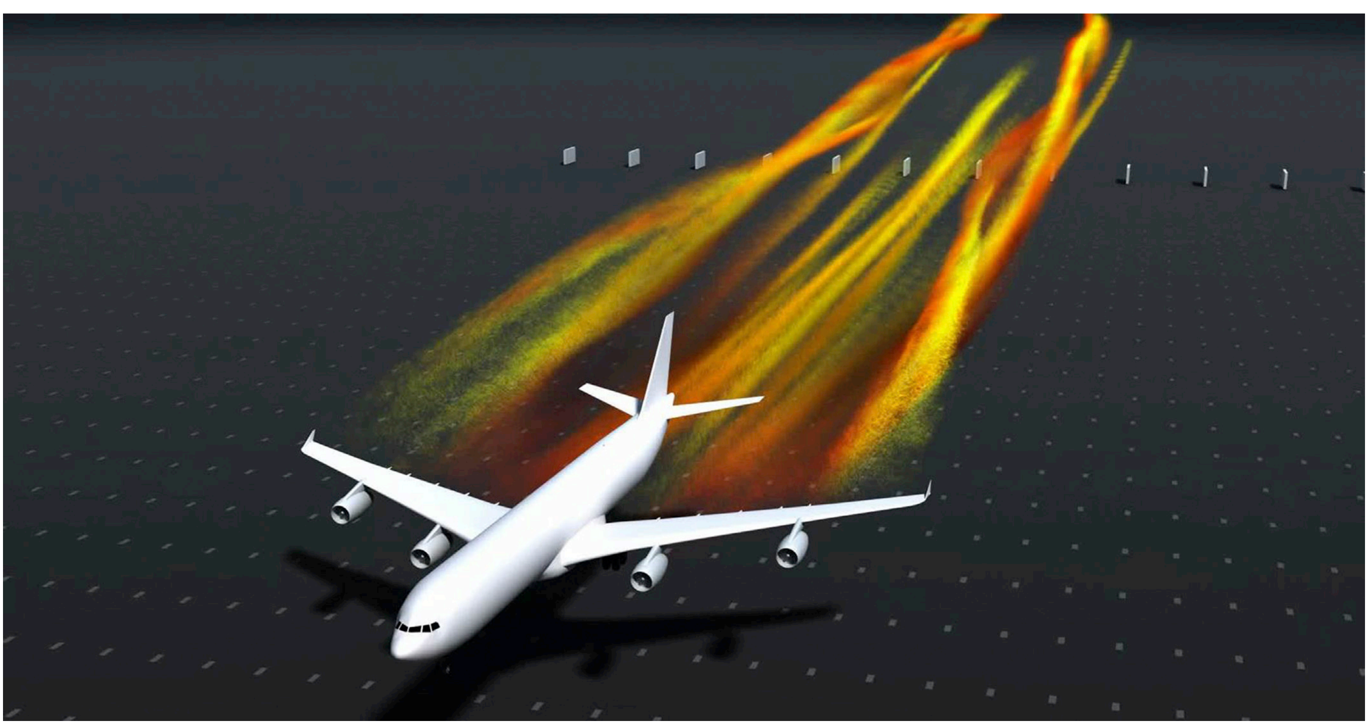

Fig. 1. Wake-vortex rollup (visualized by vorticity distribution) during final approach of aircraft in high-lift configuration [12].