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Wake vortex characteristics of transport aircraft

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ABSTRACT

The flow and flight physics of wake vortex systems has been intensively investigated concentrating on a large variety of aspects. This paper gives a brief overview on past and present wake vortex research activities such as early studies, integrated programs, model and flight tests, numerical investigations, fundamental physical aspects and alleviation strategies. Then, detailed results of the properties of the wake near field and extended near field are presented addressing typical length and time scales and especially turbulence quantities. Progressing from the near field to the far field wake instability mechanisms are explained along with their relevance for wake vortex decay. Characteristic quantities are given for the short and long wave instabilities associated with vortex merging and wakes consisting of two and four trailing vortices. A non-dimensional frequency parameter is introduced to classify the main instability types. Means for wake vortex alleviation are described aimed at influencing the wake vortex turbulence field or triggering and amplifying the inherent instabilities. The methods discussed include passive means such as the effects of spoilers, differential flap setting and four-vortex systems and active means using oscillating flaps or auxiliary devices.

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1. Introduction

Wake vortices develop as a consequence of the lift an aircraft produced to fly [125]. For a wing generating lift, the pressure on the wing lower surface is higher than the pressure on the wing upper surface. Therefore, air flows around the wing tip from the lower surface to the upper surface resulting in a strong vortex, the so-called "wing tip vortex". Further, the fluid coming from the wing upper and lower surface shows a different sense of direction at the wing trailing edge. Thus, a free shear layer or vortex sheet develops, which is connected with the respective wing tip vortex in the span direction. This free shear layer rolls up due to its self-induction together with the wing tip vortex into a single rolled-up vortex for the left and right wings, respectively. Consequently, two counter-rotating trailing vortices exist, which can exhibit cross flow velocities of up to 360 km/h in their core region depending upon flight conditions and airplane size. Those trailing vortices stay downstream up to hundred wing spans and more, before they decay due to instability mechanisms and/or due to atmospheric effects. This means that trailing vortices can have a lifespan of several minutes and a length of up to 30 km for large airplanes. The wake vortex system turns out to be far more complex in the near field region for high lift configurations, i.e. at takeoff and landing, if slats and flaps are deployed. Under such conditions further dominant vortices are present. In particular, very strong vortices may develop at the flap side edges, which still exceed the strength of the wing tip vortices [3,11].

An airplane affected by a vortex wake experiences, depending upon its position relative to the wake vortices, an upwind field, a downwind field (loss of lift) or an induced rolling moment (Fig. 1) accompanied by more or less strong velocity fluctuations [100,116,120]. In particular, for an airplane which is smaller than the one flying ahead serious consequences can arise from the wake impact: These are increased structural dynamic loads or loss of the stable flight condition, if for example, the available commanded rolling moment is not large enough to counteract the wake induced rolling moment.

The strength of the two trailing vortices, which remains after the roll-up process, is proportional to the total circulation and thus to the lift, which compensates the aircraft weight. The safety margins for the longitudinal distance between two airplanes depend therefore on their maximum take-off weight (MTOW). This criterion has been introduced in the seventies by the International Civil Aviation Authority (ICAO) [41,42,79] (Table 1). Three weight categories exist: "light" (under 7.000 kg), "medium" (7.000 kg up to 136.000 kg) and "heavy" (over 136.000 kg). Depending on the combination of ahead flying and the following airplane a distance between the airplanes from 3 to 6 nautical miles (5.56–11.12 km) must be kept [96].

These safety margins limit already today the capacity of the runways at many airports, as for example Frankfurt/Main, and thus the capacity of the entire airport. This problem will continue to intensify in view of the further estimated high growth rates of civil air traffic and scarce surfaces for the extension of existing airports or building of new airports. Concerned are, on the one hand, the manufacturers of large airplanes, and on the other hand, air traffic control and airport operators, who want to reduce the aircraft separation distances during increase in density of traffic, with a strong mixture of different types of aircraft and thus different wake vortex types, under full retention of the safety standards.

Also for military aircraft wake vortices are of particular interest because their impact can lead to considerably high structural dynamic loads [85,95]. Thereby, the formation flight, the approximation to the tanker aircraft for air refueling or flying through the wake of the opposing aircraft during air combat are of special interest.

2. Research activities

2.1. Early studies and integrated programs

The three–class categorization of aircraft separation distances made on basis of the maximum take-off weight fulfills the safety standards to all experiences. In the seventies first extensive model studies and flight tests were carried out in context with the definition of the separation distances [42,5,6,15,17,59,62,80,113]. Different overview articles inform about earlier and current research work in the area of the wake vortex problem [36,52,66,120,126]. The work presented therein takes up fundamental physical questions regarding vortex modeling, instabilities and unsteadiness. Numerous studies are concerned with the development and application of methods for the experimental and numerical simulations to represent and analyze all stages of the wake vortex lifespan (Fig. 2). Also, means to influence the wake vortex system for reducing the wake vortex hazard are addressed. A further emphasis of the investigations is on the simulation and forecast of the wake vortex behaviour in the atmosphere as well as the development and use of detection and wake vortex warning systems. In the following, an overview of these research fields is given.

In view of the relevance of the wake vortex problem for the European aircraft industry different research projects and integrated research programs were and are conducted, e.g. EuroWake (1996–1999) [73], Wirbelschleppe I/II (1999–2006) [51], C-Wake (2000–2003) [74–77], WakeNet2-Europe (2003–2006), WakeNet3-Europe (2008–2010) [140], AWIATOR (2002–2007) [63], IHK (2005–2007) [84] and FAR-Wake (2005–2007) [139]. They are concerned with the topics wake vortex forecast, detection and characterization and