[EN-022] An integrated Wake Vortex Visualization Concept for existing Cockpit Display Systems

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Abstract: Major hub airports often operate at their capacity limit and will become more and more the bottlenecks of the air transport network. Among other factors, conservative wake vortex separations during approach and takeoff have a significant impact on an airport's operation efficiency. One possibility to increase capacity is the delegation of separation responsibility from the air traffic controller to the flight crew. However, to guarantee safe operations the pilots have to obtain full situational awareness of their environment including potentially hazardous vortex traffic. This paper introduces a concept for the graphical provision of wake vortex hazard areas in existing cockpit displays. The chosen approach has been realized and integrated into an Airbus A320 cockpit simulator at the Institute of Flight Guidance of the Technische Universitaet Braunschweig. An overview of the institute's simulation environment is given, followed by a presentation of the chosen visualization concept. Results of first evaluations with pilots of commercial and general aviation are summarized. Finally, future work and further developments are addressed.

Keywords: Wake Vortex, Human Machine Interface, Pilot Assistance System, Simulation Environment

1. INTRODUCTION

Despite the global economic recession since summer 2008, current forecasts still predict a growth in air traffic worldwide [1]. As major hub airports often operate at their capacity limit today, they will become more and more the bottlenecks of the overall air transport network. There are multiple factors limiting an airport's capacity. Due to spatial restrictions, it becomes nearly impossible to expand existing airports by additional runways and other ground infrastructure, especially in areas with a high population density like Europe. Furthermore, air traffic controllers have to follow strict regulations that make it difficult to flexibly handle the current traffic situation. In this context, the large separations during approach and takeoff resulting from conservative wake vortex regulations have a significant impact on operation efficiency.

One possibility to increase capacity is the reduction of wake vortex separations between landing respectively departing aircraft. Today, air traffic controllers are fully responsible for aircraft separation. For the future concepts of free flight and Trajectory Based Operation (TBO) even the complete delegation of separation responsibility to the flight crew is projected. However, to preserve or even improve the current safety level it will become indispensable for the pilots to obtain full situational awareness of their environment including potentially hazardous vortex traffic. At the moment, no onboard system exists that would provide the required information with enough accuracy and reliability.

The Institute of Flight Guidance (IFF) of the Technische Universitaet Braunschweig is involved in several research activities dealing with the determination and graphical presentation of wake vortices. To achieve a maximum degree of usability, the integration of wake vortex information into existing cockpit displays is one possible approach.

This paper presents a visualization concept for the graphical provision of wake vortex information of surrounding aircraft in already existing cockpit displays. The chosen approach has been realized and integrated into an Airbus A320 cockpit simulator that is part of the modular aviation simulation environment of the IFF [2]. In the following section, an overview of the mentioned simulation environment is given including a short introduction of the software development framework the implemented display application is based on. After this, the visualization concept is presented. First tests were conducted with pilots of both commercial and general aviation to investigate usability aspects as well as potential increase of situational awareness. The results of these investigations are addressed, followed by an outlook on future work focusing on automated support applications for multiple approach procedures considering current wake vortex information.

2. SIMULATION ENVIRONMENT

An essential part during the development process of new concepts and systems deals with the validation and evaluation in order to ensure their suitability for real operation conditions. Because testing in a real environment might be complicated and not feasible in many situations mainly due to safety issues, simulation is a common approach.

The IFF owns a simulation environment that is used for demonstration of existing and future air traffic management (ATM) concepts and human machine interface (HMI) technologies, educational purposes as well as research activities within national and international projects focusing on the development of future assistance systems. It consists of simulators for both cockpit and air traffic control (ATC) side. While each component is standalone and can be operated individually, it is also possible to collaboratively run the whole system. In the following, the single components are briefly presented.

2.1 Cockpit and ATC Simulators

For the cockpit part, an Airbus A320 and a Grob G115 cockpit simulator are available. Both simulators are fix-based and use the Microsoft Flight Simulator X (FSX) as simulation software. The FSX is widely-used, inexpensive (but not open source) and meets the compatibility requirements of the used avionic systems simulation software packages. Another advantage is the realistic outside view and the possibility to extend its default scenery set (e.g. by a highly detailed one of a specific airport). Focusing on HMI development requires a preferably realistic visualization of the aircraft environment instead of focusing on a maximum detailed and precise flight physics simulation.

The stationary A320 simulator (Fig. 1) has a triple channel external view using three projectors, each plugged to an individual computer. This allows a viewing angle larger than 180°.

Figure 1 Displays and Instruments of the A320 Cockpit Simulator

A multi-channel audio system is used to simulate the intercom, radio messaging and warning sounds. While the physical flight model is based on the FSX, the system simulation is realized by a proprietary software package comprising all cockpit displays, input devices and their logic. The overall simulator runs on nine individual computers including one instructor station. This architecture allows the replacement of individual modules successively by self developed solutions. For the future, the IFF plans to replace the major part of the cockpit HMI and the interface between hardware and flight simulation.

The Grob G115 is built in an original cockpit of a G115 prototype. As no complex hydraulics or avionic systems are simulated, it does not use any separate system simulation software. The G115 is moveable and therefore often used as a demonstrator on expositions and other public events.

For the ATC part, the simulation environment consists of a controller working position and an airport traffic simulator. The controller working position is based on a HMI technology that has been implemented in a former research project. The display has been developed to support airport surface controllers and is currently extended to meet the requirements of an en-route controller working position. The airport traffic simulator is used to generate traffic on an aerodrome surface and for approach and departure flight phases. The position and movement information of all simulated aircraft as well as the complete communication between ATC controllers and the flight crews (e.g. clearance requests and clearances) are provided to all other components of the simulation environment using different data interfaces.

2.2 Software Development Framework

A software development framework is used as common base for the integration of new applications into the simulation environment. It is divided into two major modules. One module covers all data exchange and interconnection aspects needed for the communication of individual applications and components of the simulation environment. The other one provides functionality to support the implementation of graphical user interface (GUI) applications and simplify their integration into the onboard displays. To keep implementation efforts low, the framework wraps several other programming libraries (e.g. the SimConnect interface used for data exchange with the FSX) and unifies them in one application user interface (API).

The display module offers a set of functions that enable the researchers to setup, configure and administrate a simple GUI application capable of user interaction via several input devices (e.g. mouse, keyboard, touch-screen or levers and switches of the cockpit simulators). Furthermore, a

library of display items is created from which display applications can be assembled. Examples for display items are the artificial horizon and the altitude scale as well as smaller items like the bank markings found at top of the artificial horizon item. In other terms, each display consists of a set of graphics items that are organized in a tree data structure. Software developers have the possibility to create new graphics items or extend the functionality of already implemented ones by using common object-oriented programming paradigms.

3. WAKE VORTEX VISUALIZATION CONCEPT

Even today, wake vortices pose a serious danger for aviation and might lead to catastrophic consequences if penetrated by an aircraft. As wake turbulence is a natural result of aerodynamic lift, they can not be avoided. Thus, following aircraft have to respect separation minima that have been initially set up by the International Civil Aviation Organization (ICAO) [3] in the 1970s. Those separations are regulated by strict criteria based on the maximum takeoff weight and have proved sufficiently safe. But as they are also based on a worst case scenario (i.e. extremely calm air and no lateral winds) the vortices' decay is underestimated in most situations. Statistics [4] showed that nearly 20% of all delays in civil aviation result from these safety regulations unnecessarily limiting capacity and having a significant impact on the economic efficiency of commercial airlines.

To meet future requirements, a change of current air traffic procedures in combination with the introduction of new assistance systems is needed. As already mentioned, one possible approach is the delegation of separation responsibility from the air traffic controller to the flight crew. On condition that safe operation is still guaranteed, this gives the pilot the ability to change his trajectory by choosing an optimized flight path and reduce the separation to the preceding aircraft depending on the current wake vortex situation.

The review of existing concepts for wake turbulence visualization has shown different approaches reaching from the visualization of a detailed wake path in a perspective display to just a modified time separation given by ATC. However, no existing concept considers the design of modern airliner cockpits.

A recent research project at the IFF investigated the possibilities of providing wake vortex information to the flight crew using the primary cockpit displays of an Airbus A320 [5]. For the purpose of validation and evaluation, the developed concept has been integrated into the institute's simulation environment based on the mentioned software framework.

3.1 Wake Vortex Determination

The graphical depiction of wake vortices requires real-time information about the temporal evolution of their strength (circulation) and position. The vortices' strength primarily depends on the weight, wingspan and velocity of the generating aircraft. Their trajectory is influenced by a self-inducing part and the impact of wind. In ground proximity additional secondary as well as tertiary vortices might be generated.

For the determination of wake vortices two basic approaches are available: the physical detection by sensors like Light Detection and Ranging (LIDAR) and the prediction by mathematical models. To achieve a higher degree of accuracy, integrity and availability, the fusion of sensor and model data is also investigated [6].

In this paper the determination of the required wake vortex characteristics utilizes a prediction model called Determin-istic 2 Phase Wake Vortex Decay and Transport Model (D2P) [7][8]. The algorithm was developed by the German Aerospace Center (DLR) and is based on physical principles underlying the wake evolution mechanism calibrated with empirical data. Effects of wind, air turbulence, stratification and ground proximity are also taken into account. Model inputs are parameters of the generating aircraft as well as data of the meteorological condition. Due to the limited availability of some input parameters provided by the FSX (e.g. no turbulence information), the original algorithm was slightly modified.

In summary, the following parameters are read from the FSX using the mentioned software framework:

- weather data
  - air density
  - air temperature
  - air pressure
  - wind velocity
- aircraft data
  - position
  - orientation
  - velocity
  - weight
  - wingspan

For real operation conditions the developed system needs to be integrated into the aircraft's avionic systems to receive all required parameters for wake vortex prediction. However, all parameters are provided by already existing systems and technologies [6].

3.2 HMI Concept Description

Due to the complexity of modern flight decks and flight guidance systems, an immense amount of information must be provided to the pilots. Thus, the interface design has to meet high standards in terms of usability and inter-pretability to gain comprehensive situational awareness in a minimal time range.

Several interviews with pilots, the considerations of general HMI aspects as well as a detailed analysis of current Airbus cockpits showed that the combined use of the Primary Flight Display (PFD) and Navigation Display (ND) are best suitable for the implementation of the developed wake vortex visualization concept. Otherwise, the integration of additional information into already existing cockpit displays result in multiple requirements that have to be fulfilled. For instance, the visualization

- should fit to Airbus' HMI design and philosophy,
- should contain only absolutely necessary information,
- should be intuitive and easy to understand,
- must not overlap other indicators or look similar to other indicators to prevent mistakes,
- must not affect the display's originally intended functionality, etc.

The wake vortex visualization concept follows the already existing concepts of the Predictive Windshear System (PWS) and the Traffic Alert and Collision Avoidance System (TCAS). While the ND provides a global overview of current wake vortex situation, the PFD offers tactical information to support the pilot's decision making.

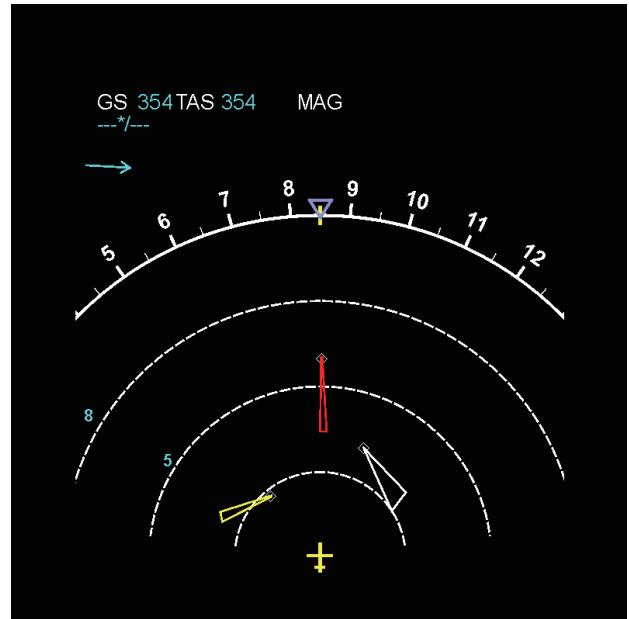Figure 2 Wake Vortex Visualization in the PFD

Figure 3 Wake Vortex Visualization in the ND

In order to prevent a wake turbulence encounter, it is not reasonable to visualize the position and strength of each individual vortex. Instead, it is adequate to display only the overall danger zone of the predicted wake vortices. The vertical position and dimension of the wake turbulence area is provided in the PFD (Fig. 2), the lateral position and dimension is presented in the ND (Fig. 3). To avoid distraction, the vortex information is only displayed if required.

Based on the symbolism and color coding of the TCAS, the wake vortex display application consists of the following three warning levels: normal (white), caution (amber) and warning (red). Depending on the time a potential hazardous wake of surrounding traffic can be reached, each danger zone is assigned to one warning level and visualized by its corresponding color. The current overall operating status equates to the most critical warning level.

In normal operation, no potential wake turbulence zone can be reached in less than 40 seconds. In this case, a visual presentation is given only in the ND. If a potential hazardous wake turbulence zone is less than 40 seconds away, the warning level is set to caution. In the PFD, one amber rectangle is displayed. Additionally, one single acoustic "wake ahead" advice is given to attract the pilots' attention to the upcoming danger. In case a potential hazardous wake can be reached in less than 25 seconds, the most critical warning level is effective. The former amber rectangle in the PFD changes its color to red and an additional amber rectangle appears (Fig. 2). While the red rectangle presents the vertical position and dimension of the wake turbulence, the amber rectangle provides infor-
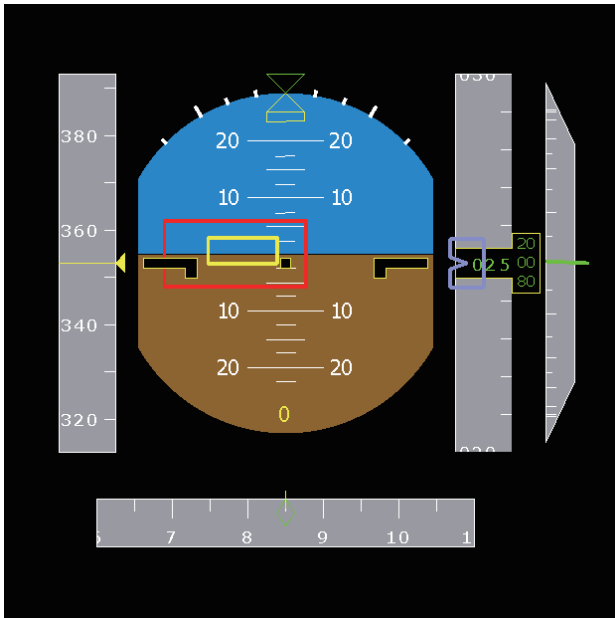
mation about the vortex trajectory. The graphical provision is supported by an acoustic "wake" output as a continuous tone. Table 1 summarizes the visual and acoustic warnings.

Table 1 Visual and Acoustic Warnings

Warning Level	Display on ND	Display on PFD	Acoustic Warning
NORMAL	No display or white polygon if requested by the pilot	-	-
CAUTION	Amber polygon	Amber rectangle	WAKE AHEAD played once
WARNING	Red polygon	Red and amber rectangle	WAKE played repeatedly

3.3 Evaluation

First tests were conducted with pilots of both commercial and general aviation to investigate usability aspects as well as potential increase of situational awareness. The evaluation comprised a presentation of the visualization concept followed by a short introduction of the cockpit simulator and mission briefing of the actual flight scenario. The mission was to perform an extended final approach on the research airport Braunschweig-Wolfsburg (EDVE). A preceding aircraft acted as wake turbulence generator whose trajectory has been recorded during a former flight with the simulator. At first, the pilots were asked to slowly approach the danger area in order to experience the different warning levels. In a next step, they should try not to penetrate the hazardous wake vortex area while undershooting the ICAO separation minima.

In summary, the developed visualization concept was considered useful and intuitive. Especially the graphical provision of wake turbulence danger zones in the ND received positive feedback. As the symbolism and color coding is based on the TCAS principles, the pilots were able to easily interpret the presented information.

Further development will mainly focus on the visualization in the PFD where two major issues have to be solved. First, it has to be analyzed whether it is sufficient to display only one rectangle in case of the warning mode as the vortex trajectory is already provided in the ND. Another aspect addresses the simultaneous use of amber and red rectangles representing two different warning levels. As Airbus cockpit philosophy allows only one warning level at the same time, this might lead to misinterpretations.

As the developed concept does not support any advisory output comparable to the resolution advisories of TCAS, the pilots were asked if such information would be reasonable. All pilots rejected this suggestion with the argumentation that a prioritization of all available advisories (i.e. TCAS, PWS and Ground Proximity Warning System) might be unsolvable.

Another aspect that was addressed by several pilots deals with the coordination of changes of the current flight path with the responsible controller due to an onboard wake vortex warning. Under existing regulations, the flight crew is not allowed to change their assigned trajectory without permission of ATC, especially on final approach. However, to react immediately the coordination and negotiation with ATC would be too time-consuming and increase the pilot's and controller's workload even more. Thus, the use of automated systems onboard the aircraft and on ground in terms of a collaborative decision making would be a suitable solution.

4. CONCLUSION AND OUTLOOK

A visualization concept has been introduced in this paper in order to improve the flight crews' situational awareness concerning hazardous wake turbulence. As projected by future operational concepts, this information enables the pilots to assume separation responsibility and increase an airport's capacity and efficiency.

The developed concept has been integrated into the already existing primary cockpit displays of an Airbus A320 simulator providing information about the position, dimension and trajectory of wake vortex danger zones. The integration into the presented simulation environment was supported by a software framework that simplifies the creation of HMI applications and unifies the data exchange between individual simulator components. The implementation of the display application has shown that programming efforts were reduced resulting in more resources available to focus on conceptual work.

The A320 simulator provided a realistic environment for the validation and evaluation of the wake vortex visualization concept by professional pilots. A next step will be the integration of the developed system into the institute's research aircraft for further experimental activities under real operation conditions. The required porting effort will be low due to the applications' unified data exchange interface based on the software framework.

Moreover, future research work at the IFF will focus on the combination of different technologies supporting the flight crew during the approach phase. That means that onboard assistance systems for an increased situational awareness (like the presented wake vortex visualization concept) will collaborate with approach guiding systems like Ground Based Augmentation System (GBAS) and ATC assistance systems. The overall goal is to have automated support applications for multiple approach procedures (e.g. different approach angles to avoid

preceding wake vortices) to give the cockpit and tower crew assistance without increasing their workload. The different subsystems developed at the IFF will be combined in the presented simulation environment to have evaluation and demonstration capabilities for these concepts toward higher degrees of automation in ATM.

5. ACKNOWLEDGMENTS

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