TOWARDS WAKE VORTEX SAFETY AND CAPACITY INCREASE: THE INTEGRATED FUSION APPROACH AND ITS DEMANDS ON PREDICTION MODELS AND DETECTION SENSORS

Shanna Schoenhals, Meiko Steen, Peter Hecker
Institute of Flight Guidance, Technische Universitaet Braunschweig

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Abstract

The integrated concept for collaboration of wake vortex prediction and measurement is introduced in this paper. This approach has the ability to increase airport and air space capacity while maintaining or even improving current wake vortex safety. The aspect of requirements resulting for the prediction model and measurement sensor is presented in detail. Implementation examples are given for ease of understanding.

1 Introduction

The forecast scenarios for air traffic evolution, despite of the recent economic developments, still predict a considerable increase of aircraft movements [1]. Therefore, the designated programs to face challenges in future air transportation, as SESAR in Europe or NextGen in the USA, put a major focus on increasing safety and capacity. Among other advances, the use of GPS to provide more accurate position information and thus enabling aircraft to fly more closely spaced without diminishing safety is considered as one important element of the future air traffic system. Only recently, in many parts of the world the Reduced Vertical Separation Minima (RVSM) procedures have brought about significant increase in en-route airspace capacity.

Nevertheless, as the impact of navigation and surveillance constraints on safe separations begins to decrease, the relevancy of safety margins required to ensure protection from hazardous wake turbulence encounters increases. Since the early 1970s, separation standards based on aircraft weight are applied to mitigate this risk. They are proven to be sufficiently safe but are also widely recognized as being very conservative, thus considerably limiting airspace and airport capacity. This conservatism is due to the fact that to date, no technology is available to predict or measure the exact position and hazard level of aircraft vortices that could be used in an operational environment.

However, considerable effort has been done in the past decades to change this situation:

Physical models to predict wake vortex behaviour in terms of decay and transport have been devised that were assessed by field measurements and extensive numerical simulations.

Also sensors to measure wake induced turbulence were developed that shall enable physical detection.

In several research projects, systems for Wake Vortex Warning, Advisory or Avoidance were designed that comprised the prediction and detection elements. It has been recognized that the principles of wake modeling and measuring are characterized by complementary capabilities and constraints that will be depicted later on. Therefore, it is apparent that an appropriate interaction between the two elements would improve the overall system performance in terms of accuracy and reliability.

The work conducted currently at the Institute of Flight Guidance (IFF) of the

Technische Universitaet Braunschweig focuses on a novel and promising fusion approach for model and sensor data. In the course of this research, capabilities and possible interfaces both of existing wake prediction algorithms and measurement equipment have been analyzed with respect to incorporation in a collaborative system.

This paper, after giving an outline of wake modeling and measurement background, will introduce the fusion concept along with the demands posed by it on the prediction model and detection sensor and discuss initial results achieved by simulations.

2 Wake Vortex Prediction and Detection

2.1 Wake Vortex Modeling

For the purpose of wake vortex modelling, two stages of the wake vortex development process can be distinguished: wake initialization and wake evolution.

The relatively short initial phase, the so-called near-field wake, can be extremely complex and its mathematical formulation requires a numerical solution for the actual configuration of the generator aircraft. To provide basic wake characteristics needed for subsequent far-field wake evolution models, this computation is often simplified by assuming elliptic span loading, resulting in a function of aircraft weight W_{AC}, span b, wing load factor s and speed V_{AC}. Thus, the calculation of the far-field wake, where it can be assumed that roll up process is completed, starts with a simple vortex pair with the initial circulation strength Γ_0

$$\Gamma_0 = \frac{W_{AC}}{\rho s b V_{AC}} \tag{1}$$

separated by the initial vortex spacing $b_0 = sb$. As a function of atmospheric conditions, i.e. background turbulence, stratification and wind, wake development is propagated in time. The effect of ground proximity and wind shear has also to be taken into account.

The models coming into focus for operational use within a fused system are the so-called fast-time models that reliably predict vortex characteristics in the far-field in terms of vortex strength and decay as well as position faster than real-time.

Some of the best known representatives are NASA's Aircraft Vortex Spacing System Prediction Algorithm (APA) [2], UCL's Deterministic Wake Vortex Model (DVM) [3] and finally the model developed by the DLR called the Deterministic 2 Phase Wake Vortex Decay and Transport Model (D2P) [4], [5]. The algorithms of all three models are based on the physical principles underlying the wake evolution mechanisms and were calibrated using empirical data from numerous experiments and simulations.

The accuracy of model predictions is highly dependent on the accuracy of the atmospheric and aircraft specific input. Due to the stochastic nature of the atmospheric environment, uncertainties can not be avoided which makes deterministic predictions quasi impossible. Furthermore, the uncertainties grow in time. Therefore, DVM and D2P have been further developed to deliver probabilistic predictions to account for the uncertainties of model input. For the first implementation of the fusion approach presented in this paper the prediction algorithms of DLR's model have been chosen, as the algorithms allowed a straightforward adaptation to a collaborative prediction and detection system.

The scheme in Fig 1 illustrates the processes performed by the D2P algorithms: with the parameters of the wake generating aircraft, including the initial position of the wake $\underline{x}_0$, D2P estimates the initial vortex state. The atmospheric conditions, namely wind vector $\underline{v}_w$, temperature T, turbulence parameter eddy dissipation rate ε and air density ρ are provided over height z. The circulation decay and vortex transport algorithms predict the vortex state for any time step t_i.

The maturity of the D2P algorithms has been assessed in several experiments (see [6], [7]) and its ability to predict vortex behaviour in an adequate way has been proved. So undoubtedly, its short term predictions deliver a good estimate of the vortex state and are available at very high update rates.

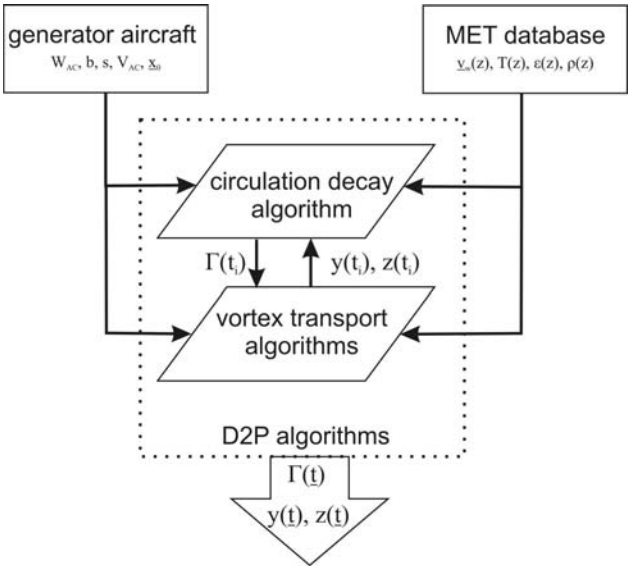

Fig. 1 D2P algorithm scheme

This is the main advantage of mathematical wake prediction together with the forecast ability.

The performance of model prediction is mainly constrained by the availability and most of all by the accuracy of input data, which is a particular problem for the on-board use as e.g. up to now no possibility exists to measure the air turbulence with adequate quality in flight with standard aircraft sensor equipment. In the operational environment of an airport, the wind measurements taken at the installed wind sensors can deviate from the wind conditions at the wake location. Also, in the current model implementations, no update of vortex state or changed meteorological conditions is foreseen, which has to be compensated with increasing uncertainty bounds and consequently loss of performance.

2.2 Wake Vortex Detection Sensors

Wake vortex detection (either ground based or for on-board applications) is realized by means of remote sensing technology. Here, especially the RADAR and LIDAR sensors come into focus, both utilizing electromagnetic waves to sense movement of the ambient air masses. For the purpose of this paper, exemplarily the wake detection by LIDAR should be explained in more detail in order to discuss the fusion issues. Nevertheless, as the application of RADAR technology for the purpose of wake detection becomes available, it should be mentioned, that the fusion concept can be adapted to this sensor in a similar way.

The LIDAR system is measuring the line-of-sight velocity of the aerosols in a certain scanning pattern. From the velocity distribution, the position of the wake vortex is determined e.g. via the slopes of the tangential velocity distribution. Fig. 2 shows the vertical velocity distribution of the left (dashed line) and right (fine solid line) vortex behind an aircraft. Both distributions overlay to the velocity distribution of the vortex pair (solid bold line). There exist several methods to determine the wake vortex circulation from this distribution (see e.g. [8]).

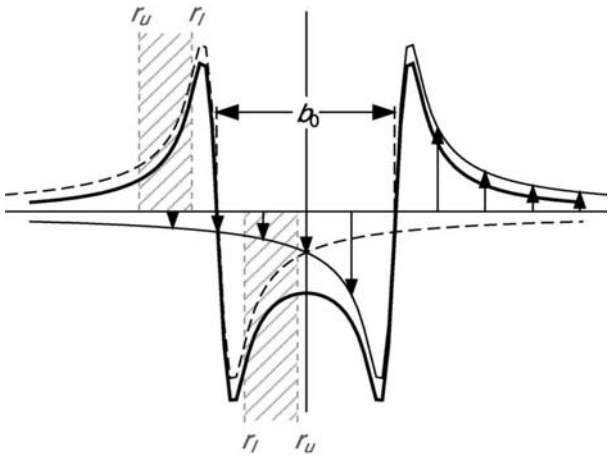

Fig. 2 Vertical velocity profile of wake vortex system [8]

The major advantage of wake vortex monitoring by LIDAR or RADAR lies in the physical turbulence detection which no model can provide. But this achievement comes at high computational burden which means that many processes have to be automated. As the flow field in an operational environment is very complex, this automated process is prone to errors like over- or underestimation or even failure of recognition of mature vortices from the velocity field and suffers in addition of the measurement noise.

As no information is available between single measurements and the update rate is relatively low, even loss of track may occur (which is an even greater problem for onboard LIDAR systems). But in the case of successful wake detection, the system has updated information on vortex state that can be used to decrease its uncertainty.

3. The Fusion Concept

Considering the complementary characteristics of wake prediction and vortex detection described above, one can assume that a collaboration between the two would result in a more reliable and accurate solution. The need to verify model predictions via additional detection sensors has already been recognized by the designers of some Wake Vortex Warning and Advisory Systems, e.g. [2], [9]. Yet, in these systems the sensor has been used either for research aims in post process (e.g. to tune the model parameters) or to identify potentially erroneous predictions of the model. They do not give any in situ feedback to the system prediction part that would improve its future forecasts. Neither is it envisioned to provide the monitoring part with a-priori information to facilitate its measurement capabilities.

Here is the essential difference of the novel fusion approach developed by the IFF. It aims to provide both available wake forecasts to the sensor part and physical detection information to the model component. Moreover, from the comparison of the complementary information obtained from prediction and measurement, the overall system uncertainty can be optimally estimated and continuously updated. This would result in reduced uncertainties, decreased false alarm rate and thus a better availability of the system for operation.

3.1 Fusion Filter Concept

The approach being currently investigated for the coupling of wake vortex prediction and detection is the use of an observation or estimation filter, the best known realization of which is certainly the KALMAN filter as described e.g. in [10]. This approach is widely used e.g. in integrated navigation of aircraft, where sensor measurements with complementary error characteristics are fused in order to obtain an optimal solution for the system states. For this purpose, a mathematical model for the system dynamics is required.

The filter generally operates in two – not necessarily alternating – steps: a time update step, where the system state is predicted based on the current state, and a measurement update which is obviously performed when new sensor data are available.

Obviously, the wake vortex modeling and measuring show similarities to the established fusion filter applications. So to transfer the fusion approach to the domain of wake vortex monitoring looks promising.

3.2 Fusion Filters for Wake Vortex Observation

The presented fusion approach is rather new for wake vortex tracking applications, therefore fundamental definitions had to be set up for this purpose. Several methods of coupling models with measurements exist. Some of them will be introduced here with the focus on the interfaces to model and sensor parts and the requirements resulting. The approaches mainly differ in the way how the models are integrated into the fused system and how the measurements are fed to the system.

First one has to distinguish between error state fusion and full state (or total state) fusion. In an error state approach, the fusion filter is estimating the errors of the model prediction, e.g. in our case the lateral and vertical wake vortex position error and the error in wake vortex strength prediction. If a modelling of error behaviour due to the errors of input parameters is implemented these inaccuracies can also be estimated and contribute to more accurate solutions.

In contrast to the error state approach, a total state system estimates the system states directly. This system would not use a separate prediction module, but would incorporate the prediction model algorithms within the fusion filter propagation step. Though, this paper will concentrate on the error state approach.

There are two possible ways to deal with the estimated error states. They can either be used to correct only the output of the model or the sensor in an open-loop setup or they can be fed back to either of the modules, which is then called a closed-loop system.

In the following, two examples of error state systems will be presented to explain the interaction between the system modules.

3.2.1 Loose-coupled open loop system

In an open-loop configuration as presented in Fig. 3, the wake vortex prediction models would be corrected by the estimated errors.

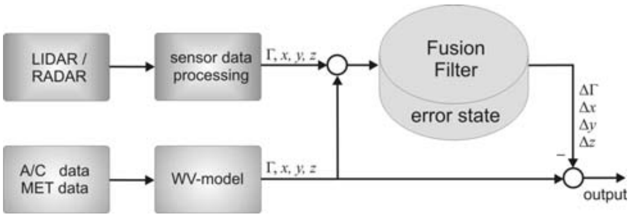

Fig. 3 Loose-coupled open-loop error state system

In this way, the sensor processing and the model algorithms remain untouched and the coupling delivers additional fused output. The result of the collaborative system (marked by the superscript $^{+}$) is generated by correcting the a priori model output (indicated by the superscript $^{-}$) with the propagated error estimations according to Equ. (2).

$$\begin{aligned} \Gamma^{+}_{output,k} &= \Gamma^{-}_{prediction,k} - \Delta\Gamma^{+}_{k} \\ y^{+}_{output,k} &= y^{-}_{prediction,k} - \Delta y^{+}_{k} \\ z^{+}_{output,k} &= z^{-}_{prediction,k} - \Delta z^{+}_{k} \end{aligned} \qquad (2)$$

The advantage is that no changes have to be implied on already existing processes and the modules can readily be used. However, as measurement and prediction will get no feedback on the accuracy of their output, they can not improve their performance. This will lead to a lower benefit than that provided by other fusion setups, but its uncertainty will be still less than the one of stand-alone prediction because of the measurement update.

The required interface to the filter would look very similar for both prediction and measurement part, containing the vortex circulation and position (*Γ, x, y, z)* at the same vortex section planes, as shown in Table 1.

The open-loop system as presented above comes into focus for airport wake surveillance systems that are already operative and therefore no changes of the existing components are possible. Applied as superimposed layer to compare and improve wake turbulence forecasts it would contribute to increasing availability and integrity of the system. That would allow increasing the operational time when the system can be used for separation reduction and thus possibly leading to augmented tactical capacity.

Table 1 Interfaces of the open-loop error state system

system component	provide	accept
model	circulation *Γ* position *x, y, z*	-
sensor	circulation *Γ* position *x, y, z*	-
filter	error estimates *ΔΓ,* Δ*x,* Δ*y,* Δ*z*	circulation *Γ* position *x, y, z*

3.2.2 Deep-coupled closed loop system

In the case that estimated errors are fed back to the prediction or sensor module, the system is operating in closed-loop mode. An example for such a system is presented in Fig. 4, incorporating both feedbacks to the model and to the sensor processing unit.

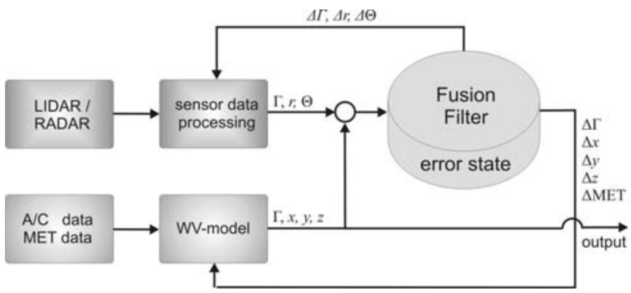

Fig. 4 Deep-coupled closed-loop error state system

The model will need an interface to accept corrections in circulation strength and wake vortex position (*ΔΓ,* Δ*x,* Δ*y,* Δ*z*). Also estimated errors in meteorological input (e.g. crosswind errors or errors of initial circulation strength) can be provided by the filter to improve the further forecasts.

In order to make this interaction possible, the model will have to allow feedback also between its single time propagation steps t_i. This means that the computation of every state will have to be discretised. For example, circulation at time step $k+1$ will be calculated according to Eq. (3):

$$\Gamma_{k+1} = \Gamma_k + \dot{\Gamma}_k \cdot dt \tag{3}$$

where Γ_k represents the circulation of the preceding time step and $\dot{\Gamma}_k$ is the decay rate. The same demand applies to position calculations. Here, the algorithms are even more complex, especially when ground effect has to be taken into account. This is usually done by introduction of secondary and tertiary vortices, whose positions and circulations will have to be corrected as well.

The values at the propagation step will then be calculated according to Eq. (4):

$$\begin{aligned} \Gamma^+_{prediction,k} &= \Gamma^-_{prediction,k} - \Delta\Gamma^+_k \\ y^+_{prediciton,k} &= y^-_{prediction,k} - \Delta y^+_k \\ z^+_{prediciton,k} &= z^-_{prediction,k} - \Delta z^+_k \end{aligned} \tag{4}$$

To aid the measurement, it is necessary to observe the errors of vortex strength, the bearing of the sensor and the distance between sensor and the gate of the wake vortex where the measurement is taken ($\Delta\Gamma$, Δr, $\Delta\theta$). The estimated error values of circulation, bearing and the distance to the wake vortex can be used to give a priori information to the sensor so that the speed of detection can be increased or that the detection is initially possible. The processing algorithms of the sensors will have to provide some information about these values and to accept and adapt the corresponding corrections in their tracking algorithms. Table 2 summarises interface requirements for model and sensor from the closed-loop setup.

The deep-coupled closed-loop approach is applicable for use with an on-board sensor as it could be linked directly to the sensor control unit and would provide the required information with a high trustworthiness. The performance would increase significantly compared to standard tracking algorithms usually available for such onboard sensors.

Table 2 Interfaces of the closed-loop error state system

system component	provide	accept
model	circulation Γ position x, y, z	corrections in: $\Delta\Gamma, \Delta x, \Delta y, \Delta z$ meteorological data e.g. wind corrections Δv, Δw initial circulation $\Delta\Gamma_0$
sensor	circulation Γ distance r bearing θ	corrections in $\Delta\Gamma$, Δr, $\Delta\theta$
filter	error estimates $\Delta\Gamma, \Delta x, \Delta y, \Delta z$ $\Delta r, \Delta\theta$	circulation Γ position x, y, z distance r bearing θ

4 Initial results using simulations

The approach described above aims at providing more accurate information on the wake vortex state than the sole prediction or only sensor measurements. In order to investigate this ability, simulations were used (see [11]) where intentionally erroneous meteorological information was provided to the model. The crosswind that is an essential mechanism for lateral wake transport was charged with a constant offset up to the normalised time $t^* = 4$. The effect on model prediction, see Fig. 5, is considerable when compared to the reference trajectory given by the simulation using correct crosswind information. Additionally, measurements of the vortices provided by a LIDAR sensor were simulated that varied around the true position of the vortex.

The fused system, implemented as an error state system, was able to estimate the error in crosswind input using the measurement updates and could provide a more accurate lateral trajectory. Consequently, the uncertainty bounds in order to cover possible wake positions can be decreased compared to sole prediction.

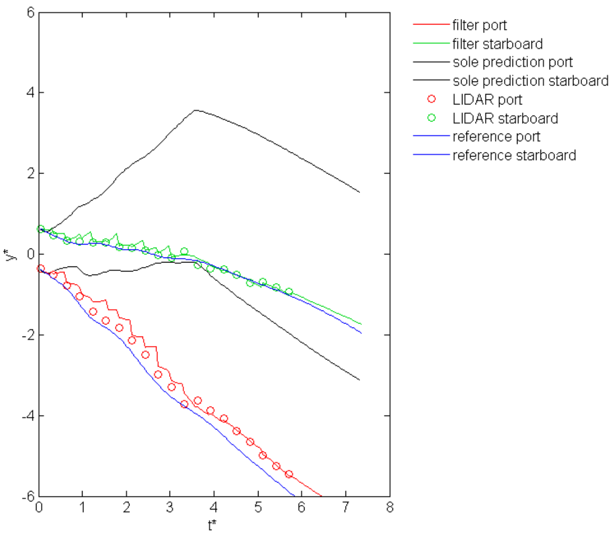

Fig. 5 Comparison of fused system and sole prediction for simulated error in crosswind determination [11]

5 Conclusions and Outlook

The concept of collaboration between wake vortex detection and measurement investigated by current studies at the IFF has been introduced. It involves the use of the KALMAN filter that has the ability to observe errors of wake propagation and detection. The benefit of this approach increases with the level of collaboration between model and sensor.

The aspect of interaction between the filter and model or sensor respectively has been discussed on two implementation examples. Whereas an open-loop approach does not require any changes in model or sensor processes or interfaces, a feedback of the estimated errors demands some adaptation of the algorithms. In return, better results can be achieved with this closed-loop system.

The fusion approach is offering a novel and promising solution for the challenging task of increasing airport and air space capacity while maintaining or even improving current wake vortex safety. It combines already existing prediction and detection techniques to provide more efficient and reliable wake vortex information. Implementation results have already shown proof-of-concept and current research focuses on elaborate modelling of propagation errors that will lead to an increase in accuracy and reliability of the fused system.

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Contact Author Email Address

s.schoenhals@tu-bs.de

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