PAPER • OPEN ACCESS

The predictive display as a means of suppressing the negative effects of wake vortex encounters

View the article online for updates and enhancements.

The predictive display as a means of suppressing the negative effects of wake vortex encounters

A V Efremov, M S Tiaglik and T V Voronka

Moscow aviation institute (National Research University), 4 Volokolamskoe Shosse, Moscow 125993, Russia

pvl@mai.ru

Abstract. The research develops a predictive information display system as a means of suppressing the negative effects of wake vortex encounters by aircraft during the landing phase. A mathematical model of aircraft interaction with a wake vortex is developed, with the effectiveness of the predictive information indication being evaluated via studies using a flight simulator.

1. Introduction

The most important requirement considered when designing aviation technology is increasing flight safety. Safety is one of the primary challenges formulated by the International Council of the Aeronautical Sciences (ICAS), the United States Federal Aviation Administration (FAA), as well as the Russian aviation technology development program. All of these documents declare the necessity of reducing the number of human factors-related accidents by 4 times.

Analysis of aviation accident statistics for the past 30 years shows that crashes caused by human factors comprise 80–85%. Of these, 65–75% are related to flight crew errors. According to the statistics given in [1], the primary factors of pilot errors are:

- errors related to manual control;
- omission of actions or incorrect actions;
- disorientation.

In general, flight accidents do not arise from a single factor, but are caused by several factors. Such factors include control system failures, suddenly changing the controlled element dynamics, as well as atmospheric disturbances: turbulence, continuous strong winds, windshear, and vortices, including those caused by previously passing aircraft.

Encountering vortices rarely leads to emergency situations in heavy aircraft, whereas flight incidents followed by passenger or crew injuries in light aircraft are a rather common occurrence. Encountering a vortex or windshear significantly complicates the piloting process, as it leads to a sudden and substantial change in attitude, airspeed and altitude, likelihood of entering a critical flight mode or a stall. In these circumstances, the pilot must quickly perform actions in multiple control channels, which significantly increases his workload.

2. The model of aircraft interaction with a wake vortex

A turbulent wake vortex caused by a previously passing aircraft is a combination of vortices formed by wake flows from various aircraft surfaces.

Aside from heavy workload, the need to achieve precision piloting induces stress, accompanied by a decrease in control precision, and accounts for a reduction in flight safety.

In order to minimize the negative effects of wake vortices, equipped airfields have controllers warning pilots about potential encounters. In this case the pilot follows the glidepath with a speed 5 knots higher and increase the glidepath angle to 3 degrees.

In this study, a four-vortex wake model, developed in [2], was used. Assuming that the vortex is constant over a period of 12–160 seconds and for providing the determinateness of the vortex action on the aircraft (providing the stationarity of external disturbances during the experiment), such a model allows to calculate three projections of wind speed in an arbitrary point (x, y, z) for the position of the vortex, described by the coordinates $y_0 = f(x)$ and $z_0 = f(x)$.

When modeling a wind caused by a vortex, it is important to take into account that in different points in space and, consequently, for different parts of the aircraft lifting surface, the wind speed is different. In this connection, the study suggests dividing the wing and tailplane of the aircraft into segments and calculating the speed and direction of wind gust and associated aerodynamic forces for each of their attitudes.

In accordance with the proposed method, the wing and tailplane were divided into 500 segments for calculating the forces and moments occurring in these segments, induced by wind action. The coordinates of these segments were calculated in the body-fixed axis system, taking into account the balance of the considered aircraft.

Since the mathematical model of wind disturbances calculates the wind speed in an arbitrary point in the normal earth axis system, determining the wind speed in each segment of the wing lifting surface requires transferring the segments coordinates into the normal earth axis system in accordance with the coordinates and attitude of the aircraft. Then, wind components are calculated for each segment position in the normal axis system.

The calculated wind speed projections for each segment of the wing and tailplane are projected into the body-fixed axis system. Knowing the proper motion speed of each wing segment and the wind speed, the angles of attack and sideslip α_T and β_T were determined, induced by wind action in each of the segments.

Based on the initial angles of attack and sideslip α and β, the angles induced by the wind α_T and β_T, as well as on the aerodynamic characteristics, the increments of aerodynamic forces were determined, in accordance with the relations:

$$\Delta F_{xc} = qS_c(C_x(\alpha_T) - C_x(\alpha)),$$

$$\Delta F_{yc} = qS_c(C_y(\alpha_T) - C_y(\alpha)),$$

$$\Delta F_{zc} = qS_c(C_z(\alpha_T) - C_z(\alpha)).$$

After calculating the forces increments in each segment, the increments of moments were calculated.

$$\Delta M_{xc\,i} = X \cdot \Delta F_{z\,i} - Z \cdot \Delta F_{y\,i},$$

$$\Delta M_{yc\,i} = X \cdot \Delta F_{x\,i} - Z \cdot \Delta F_{z\,i},$$

$$\Delta M_{zc\,i} = X \cdot \Delta F_{y\,i} - Z \cdot \Delta F_{x\,i}.$$

Here, X, Y, Z are the coordinates of the wing and tailplane segments in the body-fixed axis system.

In order to use the obtained increments in the mathematical model of aircraft motion, the calculated increments of forces and moments are added up.

$$\Delta F_x = \sum_{i=1}^{500} \Delta F_{xi}, \ \Delta F_y = \sum_{i=1}^{500} \Delta F_{yi}, \ \Delta F_z = \sum_{i=1}^{500} \Delta F_{zi};$$

$$\Delta M_x = \sum_{i=1}^{500} \Delta M_{xci}, \ \Delta M_y = \sum_{i=1}^{500} \Delta M_{yci}, \ \Delta M_z = \sum_{i=1}^{500} \Delta M_{xci}.$$

The developed mathematical model of interaction between the aircraft and atmospheric disturbances, unlike the standard models where wind disturbances act on the center of pressure, allows to take into account the different wind action on different parts of the aircraft lifting surface, both in terms of force and direction.

3. Developing the means of suppressing the negative effects of wake vortex encounters

This study considers the predictive display as one such means, with a programmed path motion (a glidepath with the glidepath exit segment up to touchdown) presented on the screen as a three-dimensional corridor with a predictive window moving in the corridor at the speed of the aircraft and located at a distance (or predictive time T_{np}) chosen so that it ensures the minimum variance of glidepath tracking error.

In accordance with the method described in [3], the selection of the time T_{np} was carried out considering the compensatory pilot-aircraft system. The time is determined by the distance $L_{np} = T_{np}V$ between the pilot's eye and a plane (predictive window) located in the corridor covering the programmed path motion (Figure 1).
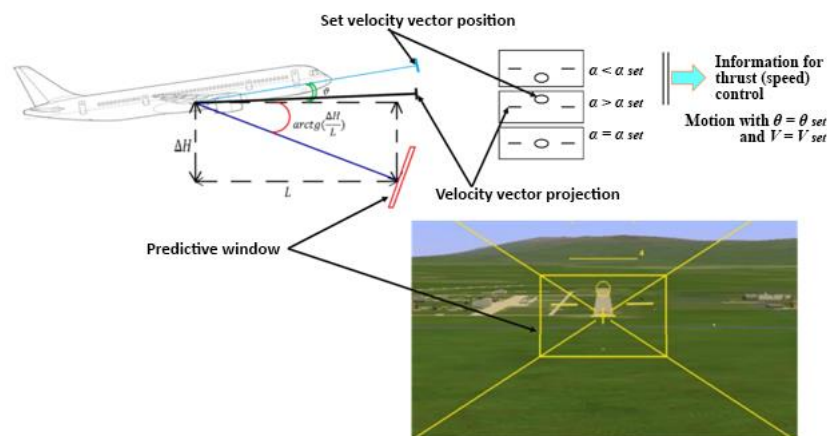

Figure 1. Predictive display.

In addition to the corridor, the display also shows a mark determining the set position of the velocity vector (see Figure 1), corresponding to the set landing speed, having the form of a fixed circle, which the pilot aims to align with the center of the predictive window using the control stick.

An important task during glidepath motion is holding the set airspeed. When performing a landing, the airspeed is close to the minimum, and the flight path angle control may become inverted under the influence of disturbances. Pulling the stick back will lead to a downward motion of the aircraft, because an increase in the angle of attack and induced drag divergence lead to a decrease in speed [4].

This peculiarity forces the pilot to simultaneously operate two controllers: the control wheel or control stick — for changing the pitch angle — and the thrust lever — for holding the airspeed and keeping a constant angle of attack.

At that, thrust control requires displaying on the screen the information on the difference between the trim and current angles of attack, proportional to the distance between the set velocity vector position and the current velocity vector position.

Thus, when deflecting the control stick, the pilot aims to align the set velocity vector position with the center of the predictive window, and, by operating the thrust lever, he aligns the velocity vector with the set velocity vector position mark.

This way of presenting flight information is applicable in the absence of continuous vertical wind gusts. In case of such gusts, if the velocity vector indicator goes below or above the set velocity vector value, and the airspeed matches the set speed, the pilot must align the velocity vector with the center of the predictive window and hold the set airspeed by referencing the speed indicator.

4. Conducting experimental research for evaluating the effectiveness of the information display system

The experimental research was carried out using the MAI flight simulator, equipped with a stereoscopic semi-panoramic visualization system, with the predictive display image being projected onto the external environment (Figure 2).

Figure 2. MAI flight simulator.

In the research, the following aspects were considered:

- the influence of the weight of a previously passing aircraft on the effects of a wake vortex encounter;
- the influence of the distance between a vortex and the runway;
- minimization of the effects of a wake vortex encounter when informed about it by the ground services.

During the investigation into the effects of "vortex generator" aircraft, two craft were examined: the A380 weighing 258 tons and the Legacy 450 weighing 14 tons. It is shown that increasing the weight of a "vortex generator" aircraft by 18 times leads to an average increase in the spread of glidepath deviations by 1.5 times. However, extensive use of the developed display by the pilot allows to perform piloting with standard deviations of the coordinates H and Z relative to the glidepath not exceeding 2 meters (Figure 3).
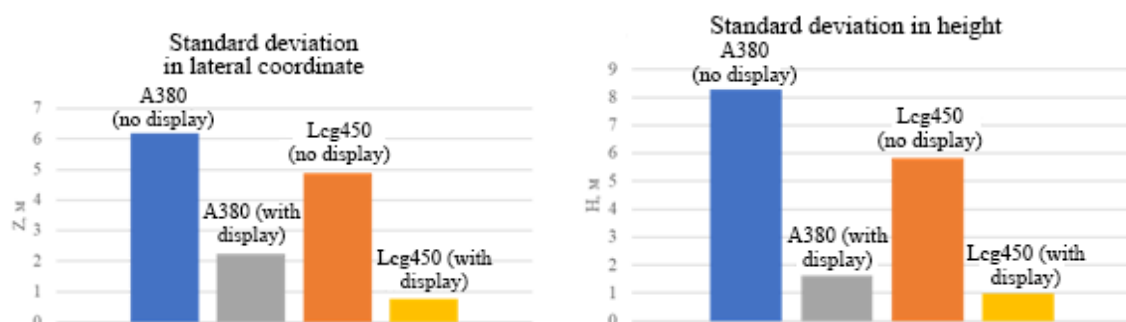

Figure 3. Glidepath tracking accuracy.

When researching the influence of the distance between a vortex and the runway, in addition to glidepath deviations, the probability of a pilot making the decision to land was estimated. For a pilot authorized to perform Category IIIA operations, the decision height for landing is 30 m. It is considered that a pilot can perform the landing if the deviation from the glidepath does not exceed 3.7 meters in height, 22 meters in the lateral coordinate, and 5 knots in speed.

The study considered two vortex positions: at a distance of 3 and 1.3 km from the runway threshold. The results of the research show that the probability of a pilot making the decision to land, calculated based on the above conditions with the vortex located at a distance of 3 km, is 55%, whereas in case of the vortex located at a distance of 1.3 km, it is merely 8%. Using the proposed indication allows to increase the probability of the pilot making the decision to land up to 95 and 46% with the vortex located at a distance of 3 and 1.3 km respectively. At that, the deviation from the glidepath will not exceed 3 meters in height and 5 meters in crossrange (Figure 4).
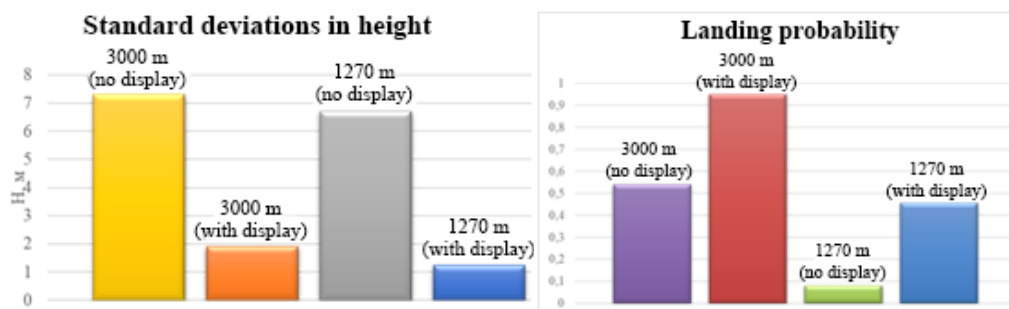

Figure 4. Glidepath height tracking accuracy and landing probability.

In addition, studies were carried out demonstrating the effectiveness of pilot warning by the controller about the presence of a wake vortex on the glidepath. If the pilot has been warned about a wake vortex, he increases the glidepath angle from 2.66 to 3 degrees and increases the approach speed by 5 knots. The studies were conducted with and without the predictive display. During research, the distance of the vortex relative to the runway was also changed.

It is shown that with the wake vortex located at a distance of 1.3 km from the runway threshold, complying with the ground services recommendations leads to an increase in the probability of the pilot making the decision to land by 4 times up to 32%. However, with the vortex located at a distance of 3 km, the probability of landing decreases from 55 to 45%, which is attributable to the complexity of tracking a steeper glidepath and high approach speed.

Using the predictive indication in conjunction with the warning allows to increase the probability of landing in the presence of a vortex close to the runway from 46 to 62 %. If the vortex is located at a distance of 3 km, the warning insignificantly reduces the probability of landing from 95 down to 90% due to high approach speed.

Regarding glidepath tracking accuracy, using the predictive display allows to ensure a glidepath deviation of no more than 4 meters in height and no more than 2 meters in crossrange (Figure 5).
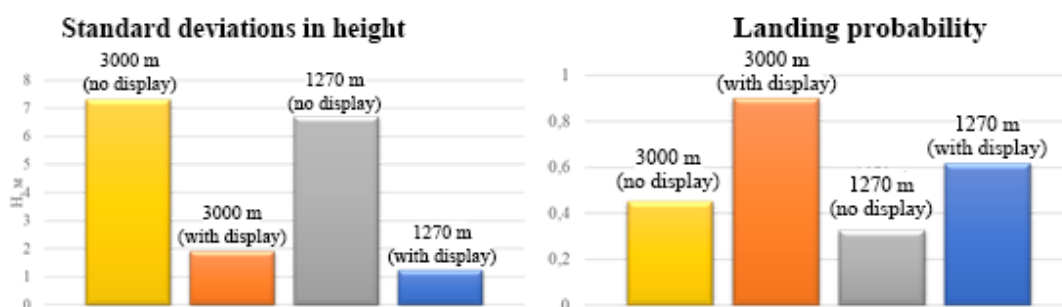

Figure 5. Glidepath height tracking accuracy and landing probability.

5. Conclusion

For the purpose of minimizing the negative effects of wake vortex encounters, a predictive information display system is proposed, whose parameters were selected by means of mathematical modeling of the pilot-aircraft system.

The experimental research evaluating the effectiveness of using the developed predictive information display system in a wake vortex encounter was carried out using a flight simulator. It is shown that using the indication allows to keep the spreads relative to the glidepath within 1.5–2 meters for varying intensity and vortex position relative to the runway and allows to increase the probability of the pilot performing the landing by 1.5–2.5 times on average.

Acknowledgements

References

[1]   *Safety Report Edition* 2018, IATA 55
[2]   Voevodin A V 2014 Applications of the Wake Vortex Mathematical Model *Trudy TsAGI* 2730.
[3]   Efremov A V and Tjaglik M S 2011 *The Development of Perspective Displays for Highly Precise Tracking Tasks* Advances in Aerospace Guidance, Navigation and Control   ed Holzapfel F and Theil S (Springer)
[4]   Efremov A V, Zakharchenko V F, Ovcharenko V N, Sukhanov V L, Shelyukhin V F and Ustinov A S 2011 *Flight Dynamics* ed Bushgens G S (Moscow: Mashinostroyenie) 776