AUTOMATED PILOT ASSISTANCE FOR WAKE VORTEX ENCOUNTERS

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OVERVIEW

Wake vortices pose a possible hazard for encountering aircraft in all phases of flight. Hence wake vortex encounters are to be avoided in any case. In case of an unintended wake vortex encounter special aircraft controllers can act as a safety net. Such an active wake vortex control system is being developed by the DLR Institute of Flight Systems based on feed-forward disturbance compensation. The control system has been tested with offline and pilot-in-the-loop investigations as well as with flight tests.
It can be shown that the aircraft response can be improved significantly if a specific wake vortex controller is active. For the subjective assessment of the wake vortex encounters a dedicated pilot rating scale has been developed. The results show a clear tendency that the wake vortex controller improves the situation.

ZUSAMMENFASSUNG

Wirbelschleppen stellen in allen Flugphasen eine mögliche Gefährdung für einfliegende Flugzeuge dar. Daher sind Wirbelschleppeneinflüge in jedem Fall zu vermeiden. Für den Fall unbeabsichtigter Wirbelschleppeneinflüge können spezielle Flugregler eine Sicherheitsfunktion darstellen. Solch ein aktives Wirbelschleppensteuerungssystem wird am DLR Institut für Flugsystemtechnik basierend auf dem Konzept einer Vorsteuerung zur Störungskompensation entwickelt. Das Steuerungssystem wurde mit offline und pilot-in-the-loop Simulationen untersucht, sowie mit Flugversuchen.

Es kann gezeigt werden, dass die Flugzeugreaktion deutlich verbessert werden kann, wenn eine spezifische Wirbelschleppensteuerung aktiv ist. Für die subjektive Bewertung von Wirbelschleppeneinflügen wurde eine spezielle Bewertungsskala entwickelt. Die Ergebnisse zeigen eine klare Tendenz, dass die aktive Wirbelschleppensteuerung die Situation verbessert.

1. INTRODUCTION

Active aircraft controllers specifically designed to cope with (unintended) wake vortex encounters can handle the vortex imposed forces and moments in order to alleviate the induced aircraft reaction [25]. Based on the availability of forward looking sensors an active wake vortex control system can be established with feed-forward disturbance compensation. This approach has been investigated with offline and pilot-in-the-loop simulations as well as with flight tests.

These flight tests have been conducted with DLR's fly-by-wire test aircraft ATTAS (Advanced Technologies Testing Aircraft System, FIG 1) using in-flight simulation. ATTAS is particularly designed for this task. During the in-flight simulation the computers onboard the real test aircraft simulate a wake vortex encounter and the real aircraft acts accordingly, flying through a 'simulated vortex.'

FIG 1. DLR test aircraft ATTAS (Advanced Technologies Testing Aircraft System)

2. ROLL CONTROL RATIO FOR ASSESSMENT OF WAKE VORTEX ENCOUNTER SEVERITY

Especially for approach and landing wake vortex encounters are typically nearly parallel. In that case the dominating effect is the rolling moment induced by the wake vortex [2]. This is particularly true for the outer regions of the wake vortex, where the aircraft reaction can possibly be alleviated, as the stronger effects of the core region cannot necessarily be compensated extensively. For that reason the definition of a roll control ratio (RCR) based on the wake vortex induced rolling moment taking into account the controllability of the encountering aircraft is a measure to assess the severity of the wake vortex encounter [22], [23], [24]. The magnitude of wake vortex induced rolling moment $C_{l,WV}$ is related to the maximum possible roll control power $C_l(\delta_{a,max})$ [4], [21]:

$$(1) \quad RCR = \frac{C_{l,WV}}{C_l(\delta_{a,\max})}$$

The worst case is the quasi stationary flight parallel to the vortex axis, because here the wake vortex is permanently acting on the aircraft.

3. CONTROLLER CONCEPT

3.1. Principles

The commonly accepted position regarding wake vortices is that no planned wake vortex penetration is permitted [1]. However, unintended wake vortex encounters may occur, not necessarily being unacceptable [15], [20]. For those encounters special wake vortex controllers could assist the human pilot. The pilot will stay in the control loop and has guidance authority while the vortex controller is active. However the vortex controller has the authority to use up to 100% of the available control power.

It is desirable that the vortex controller system does not change the aircraft handling. This is the case for feed-forward controllers.

For approach and landing parallel-like encounters are typical, which can also occur in other flight phases. Especially for these encounter situations the wake vortex induced rolling moment is the dominating effect [2], [3].

The idea is to measure the wake vortex flow field and feed this information into the vortex controller to create appropriate counteracting control commands. It is assumed that flow field can be determined in spanwise direction of the wake encountering aircraft. In principle this can be done with flow probes mounted on the encounter aircraft or by scanning the flow field upstream of the wake encountering aircraft. The latter has the advantage that system time delays can be accounted for. A disadvantage can be that the flight path of the aircraft does not exactly match the measured positions of the flow field and the control commands are not based on the actual vortex flow field.

In principle forward measurement can be achieved with LIDAR technology (light detection and ranging), laser measurements based on the Doppler effect (like RADAR). Wake vortex measurements are successfully performed with ground based LIDARs, also in axial direction [16], [17], [18]. Airborne LIDAR wake vortex measurements have also been demonstrated successfully for smoke-seeded vortices [19].

3.2. Feed forward concept

The aircraft reaction during wake vortex penetration can be improved by a pilot assistance system based on a feed forward control concept. This principle of disturbance compensation has the advantage that the aircraft handling characteristics remain unchanged. The control system is only active if an external disturbance is detected. For this concept (FIG 2 and FIG 5) it is assumed that the airflow in front of the aircraft can be measured by a forward looking sensor [4].

The feed forward concept reacts based on the predicted wake vortex velocity flow field V_{WV}, which is determined with the measured airspeed V and the flight path velocity V_K. The mean wind speed V_W must either be known or neglected.

(2) $V_{WV} = V_K - V - V_W$

The velocity field is fed into an aerodynamic interaction model which calculates the wake vortex induced forces and moments. As aerodynamic interaction model the strip method is used, where the lift generating surfaces are subdivided into sections for which the vortex influence is determined. This method was deemed feasible in [5], verified against windtunnel tests in [6] and validated with flight test data in [7] and [8]. The moments are then used with an inverted aerodynamic model to command appropriate control inputs to compensate the aircraft response due to the vortex.

3.3. Combination with autopilot

The feed forward concept in combination with an autopilot is analysed with an offline simulation. It comprises the description of the vortex generation and aging, the representation of the wake vortex induced velocity distribution and the modelling of the encounter aircraft reaction with the aerodynamic interaction model. The 6 degree of freedom simulation of wake vortex encounters is described in more detail in [4] and [9]. In order to maintain the required flight path a regular autopilot/auto-throttle system [4] (based on a model following controller concept) is applied.

The simulated aircraft is a Do 128 aircraft (ICAO class 'light', MTOW = 4.4 t). The sensors are modelled ideally so that the exact disturbance is known to the assistance system. FIG 3 shows an example flight passing vertically through a wake vortex flow field, with autopilot only in blue and with a combination of autopilot and wake vortex controller in red. The vortex generating aircraft is a category 'medium' aircraft (MTOW = 94 t) with a vortex age of t = 50 s. The side view and the top view show the flight path with the wake vortex encounter scenario. The reference flight path (green dashed line) is inclined with 3° to represent an approach situation and the wake vortex (black dashed line) is aligned horizontally. The time histories show the bank angle and the aileron command normalized with the maximum value.

While the autopilot is able to cope with the wake vortex to a certain degree, the pilot assistance system improves the situation significantly, for example with respect to flight path deviations and bank angle.

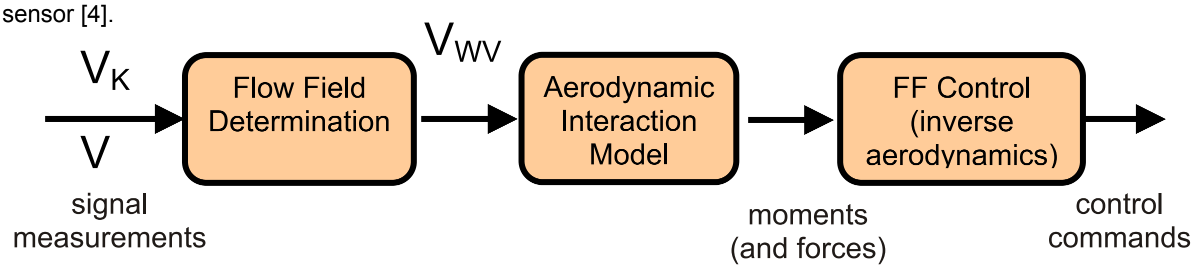

FIG 2. Feed forward concept overview

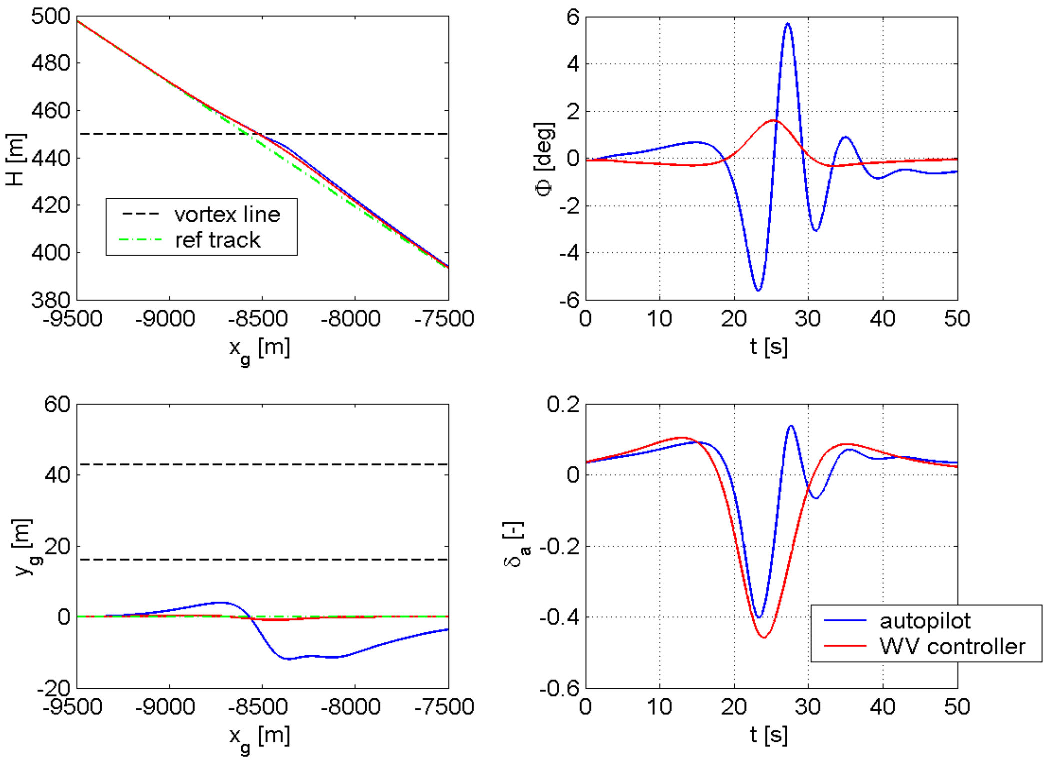

FIG 3. Flight track and parameter time histories of a flight through wake vortex flow field: side view and top view, bank angel and aileron command (offline simulation with regular autopilot and combination autopilot wake vortex controller)

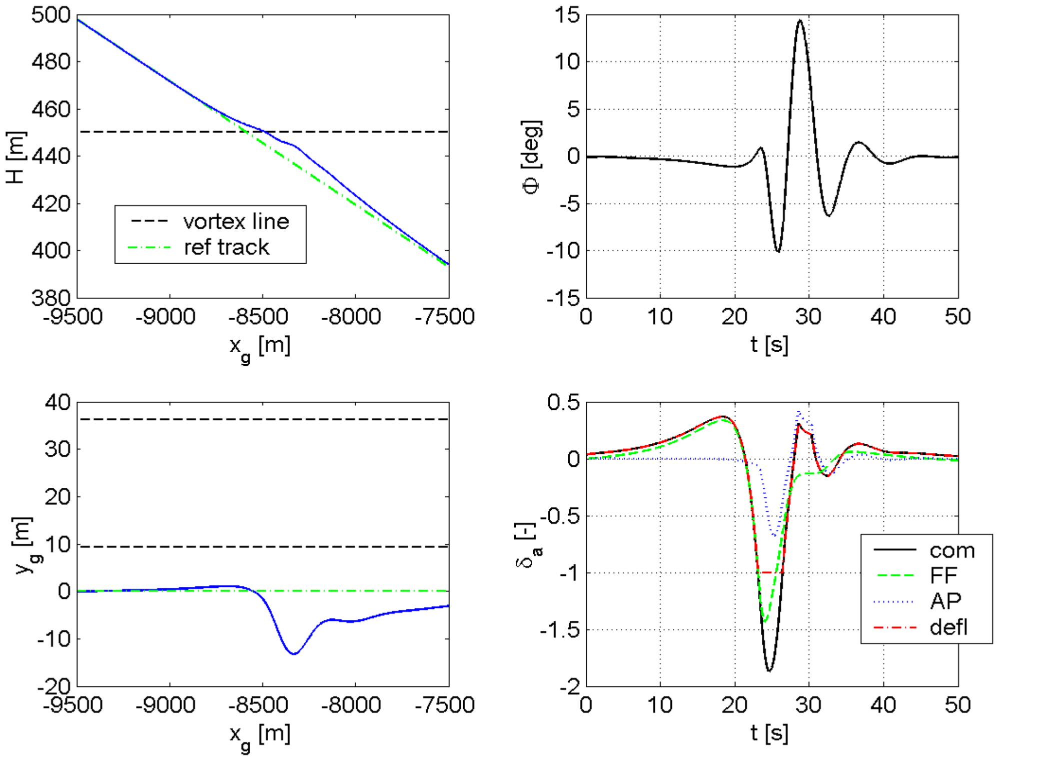

FIG 4. Flight track and parameter time histories of a flight through wake vortex flow field: side view and top view, bank angel and aileron command components and actual deflection (offline simulation with autopilot plus wake vortex controller)

FIG 4 shows a wake vortex flow field penetration with the same scenario as above but for a reference flight path closer to the wake vortex and hence higher forces and moments imposed on the encountering aircraft. The aircraft reaction is stronger (bank angle up to 15°), but still well acceptable due to the assistance system. The components of the aileron commands are shown for the feed forward command due to the vortex disturbance ('FF', green dashed line), the autopilot due to flight path and state deviations ('AP', blue dotted line) and the resulting overall command ('com', black solid line). The actual aileron deflection considering actuator dynamics and limitations are shown in red ('defl', dashdotted). The feed forward and overall commands exceed 100% for a few seconds and are consequently limited during that time. Despite the strong disturbance the resulting aircraft reaction is very satisfactory.

The results of the offline simulations with autopilot for different encounter scenarios, vortex generators and strengths generally suggest that the concept of the assistance system is appropriate for wake vortex hazard alleviation.

4. ACTUATOR DYNAMICS

Investigations with offline simulations showed that no extra demands for actuator dynamics compared to existing systems result from the wake vortex controller [12]. The overall system delays must not be too large ($\Delta t < 0.25$ s) which holds for present systems. In any case the dominating factor is the limited available roll control power rather than actuator dynamics.

5. SENSOR MEASUREMENT CONCEPT

Different forward looking measurement strategies were investigated with offline simulations [13]. Various concepts for the measurement direction and dimension in combination with data processing concepts have been developed (TAB 1).

concept	measurement direction	measurement dimension	data interpolation
1	airframe fixed	1D (line)	no
2	air path fixed	1D (line)	no
3	air path fixed	1D (line)	wing span direction
4	air path fixed	2D (plane)	wing span and vertical direction

TAB 1. Forward looking measurement strategies

The first approach is to measure the air flow in an airframe fixed direction at positions along a line in wing span direction (concept 1). Here it is assumed that the measured wake vortex velocities apply delayed at the aircraft wing. To enhance the flight path prediction quality the measurement direction is chosen along the current flight path (concept 2). For concept 3 the actual wing position is interpolated within the measurement points. To account for vertical flight path deviations a two dimensional pattern is scanned in front of the aircraft and the wing position is interpolated (concept 4)(FIG 5).

A comparison between the four sensor measurement concepts is shown in FIG 6. The absolute value of the maximum bank angle, which occurred during a wake vortex penetration is plotted against the measurement distance.

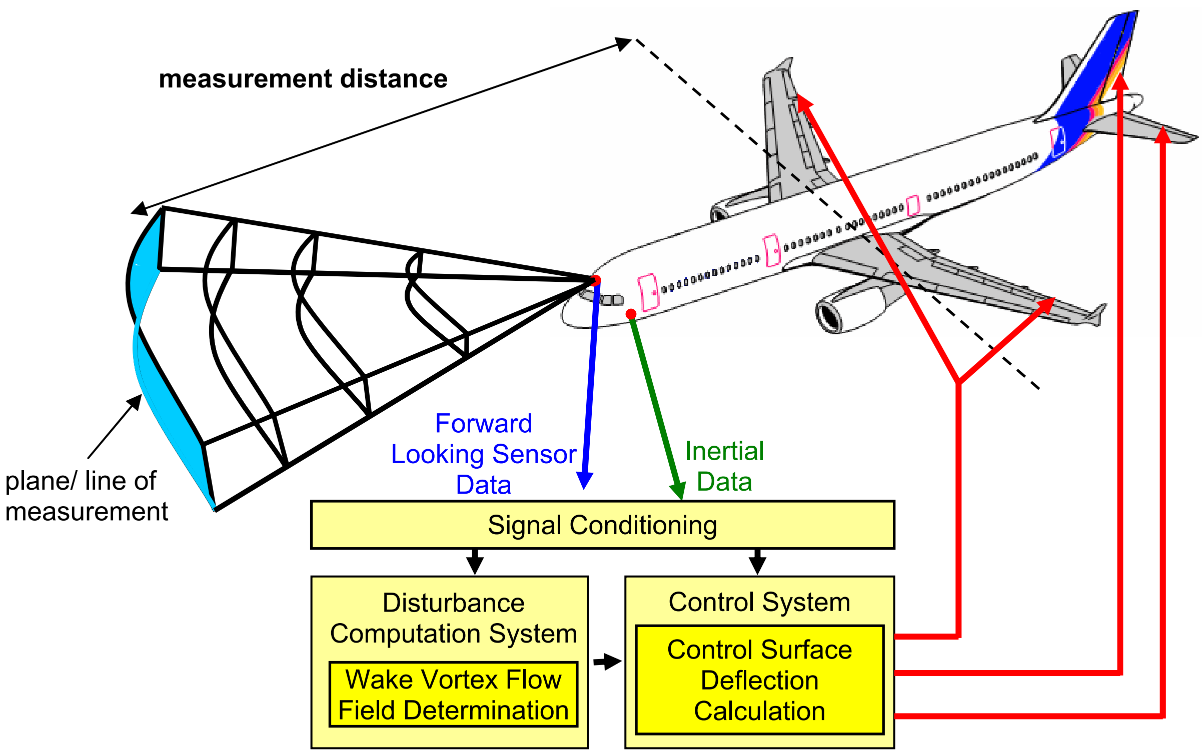

FIG 5. Forward Looking Sensor Concept

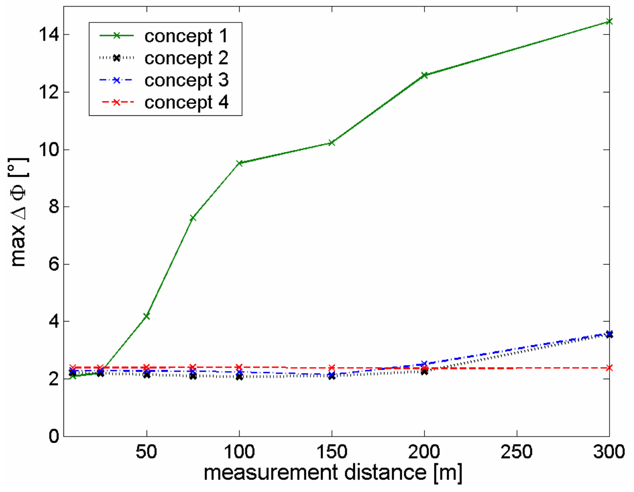

FIG 6. Effect of measurement distance on bank angle

It is obvious that the flow field has to be scanned in air path direction. The best results were achieved with the two dimensional measurement and interpolation of concept 4. Further investigations yielded a required sampling rate of f > 3Hz. The horizontal grid size for the measurements should be less than 10% of the encounter aircraft wing span. The horizontal size of the measurement plane should be at least 2.5 times the wing span and vertically at least 100% of the span.

6. PILOTED WAKE VORTEX ENCOUNTERS

Experiments in real flight offer the most realistic simulation environment. This is achieved by means of in-flight simulation. The DLR testing aircraft ATTAS (Advanced Technologies Testing Aircraft System, FIG 1) is specifically designed for this task. The real aircraft acts like the simulated aircraft (in this case the same aircraft type as the real aircraft), which encounters the wake vortex. The experimental pilot is flying the simulated aircraft using real controls. These inputs are fed into the onboard computers stimulating the model aircraft which reacts on the inputs and on the effects of the virtual wake vortex flow. The resulting model aircraft states are fed into the model following control system. The model following controller generates the control surface deflections of the (real) host aircraft which are necessary to make the host aircraft behave like the simulated aircraft. So the flight states of the host aircraft experienced by the experimental pilot are matching the flight states of the simulated aircraft. The feasibility of wake vortex in-flight simulations was already demonstrated [14], exhibiting a good simulation fidelity for an RCR at least up to 50%.

Manually controlled wake vortex encounters in an authentic environment including air traffic control and other traffic permit a subjective pilot evaluation in addition to the objective data analysis.

The encountering aircraft (ATTAS) type is a VFW614 (ICAO class 'medium', MTOW = 21 t). The vortex generating aircraft is a category 'medium' aircraft (MTOW = 94 t) with a vortex age of t = 50 s. The experiment scenario begins 6 nm before runway threshold and consists of an ILS approach and the landing (FIG 7).

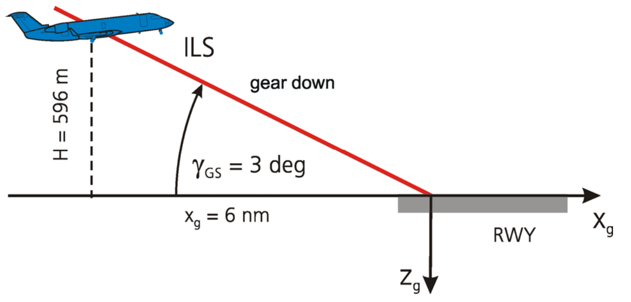

FIG 7. Approach scenario (side view)

The pilot ratings for each approach comprise four categories: aircraft control, demands on the pilot, aircraft excursions from flight state and path and over all hazard. The rating scale is graduated into four levels, with a rating of 1 denoting an uncritical case and a 4 denoting an unacceptable one (FIG 8). Ratings of 1-3 are considered acceptable.

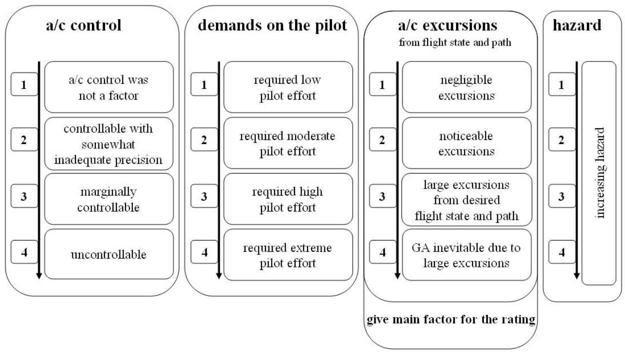

FIG 8. Pilot rating scale [10], [11]

FIG 9 shows the effect of the pilot assistance system on the pilot average ratings. The results come from three in-flight simulation (IFS) flight tests with time fixed wake vortex disturbances showing a maximum required roll control ratio of RCR = 0.5. The sensors are modelled ideally so that the exact disturbance is known to the assistance system. Altogether 9 approaches were conducted in fine weather, 7 approaches were executed in IMC conditions and 4 in light turbulence. Although the diagram is based on only 20 approaches (12 approaches with assistance system, 8 without) the tendency of improved rating can clearly be seen when the automatic controller is engaged.

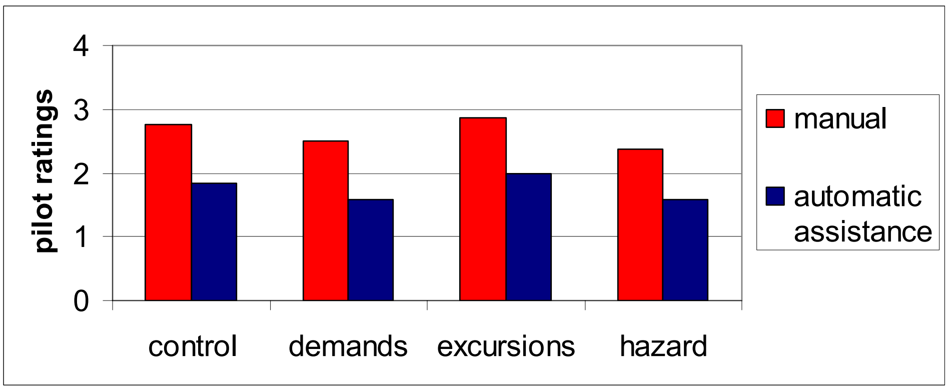

FIG 9. Pilot ratings for wake vortex encounters

7. CONCLUSION

Automatic control systems can improve the aircraft behaviour during (unintended) wake penetrations by supporting the pilot's control task. This was shown by offline simulations and piloted simulations in real flight (in-flight simulations).

Wake vortex specific pilot assistance increases safety since more severe encounter situations can be coped with in an acceptable way. With regard to the implementation of larger aircraft types and the worldwide attempt to revise (and decrease) wake vortex separation distances dedicated automatic control systems can play a major role concerning safety by providing a safety net.

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