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Ground-Effect Identification and Autoland System Validation from Flight Data

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Among the numerous applications of aircraft identification, autopilot design and certification is one of the most complex, requiring a very high level of model representation and accurate aerodynamic characterization. All throughout the aircraft lifetime, automatic landing system calls for an intensive use of high-fidelity simulation, particularly near the ground. A special identification procedure is necessary to tune the autoland control laws accurately in a short time. During the design phase or certification process, and later on for crew training or inservice incident analysis, simulation incorporating models updated by system identification is the reference for engineering evaluation. This paper presents the process used inside the Airbus company to validate an automatic landing system and provides an overview of ground-effect identification. This process is today an alternate means to expensive flight testing.

Introduction

AUTOMATIC landing system is one of the complex and critical aircraft systems and also difficult to model. Its tuning necessitates extensive tests under various conditions because it has to fulfill multiple criteria simultaneously, including some conflicting ones such as high performance and comfort. Not only all aircraft loadings (weight and balance) and configurations (flap settings), but also all of the airport characteristics [runway elevation, size and profile, instrumental landing system (ILS) characteristics], and above all, the turbulence and wind conditions (intensity and direction) have to be tested. For these reasons, the development of an automatic landing system calls for an intensive use of the simulation. Consequently, a high level of fidelity of simulation models is an essential factor in the design and certification activities.

System-identification techniques have been successfully used in the past to identify ground effect from flight data.[1−4] The main aim of this paper is to bring out clearly the importance of the aircraft identification process adapted at Airbus to successfully develop aircraft critical system.[5] As a typical example, an automatic landing system is considered for demonstration purposes.

Starting with a brief presentation of the simulation tool used for the automatic landing, the paper then provides an overview of the ground-effect identification process, followed by a description of the current applications of the automatic landing simulation. Finally, a means of compliance for demonstration of automatic landing at high elevation runway is proposed, which exploits the high-fidelity simulation incorporating models identified and tuned from flight data.

Automatic Landing Simulation Tool

The simulation software called SIMPA (Simulation du Pilote Automatique) is a toolbox including a user-friendly control interface (configuration management, data processing) and a desktop simulator, which simulates flight in six degrees of freedom. This tool is used for 1) autopilot development, 2) aircraft model identification, 3) simulation-based certification [go-around performance, automatic-landing performance, rollout performance, and wind shear warning nuisance rate, according to joint aviation authority (JAA) and federal aviation administration (FAA) requirements],[6,7] and 4) analysis of inservice problems.

The SIMPA tool, a software common for the complete Airbus family, meets the following operational requirements: 1) representative of aircraft behavior and its systems, 2) ability to simulate various flight situations, 3) user-friendly software, 4) easy and safe autopilot control laws coding, and 5) reduced execution time.

Simulation Capabilities

SIMPA enables simulation of various flight phases coupled to the autopilot (including cruise, approach and landing, rollout phases) with all modes and target changes during these phases in compliance with the actual aircraft operational logic. Furthermore, it allows statistical analysis of the simulated responses, for example, computation of mean value, standard deviation, minimum value, maximum value, correlation plots, histograms, etc. of specified variables (e.g., touchdown distance, touchdown vertical sink rate, maximum glide and lateral deviations during rollout).

Aircraft and Systems Modeling

The core of this software tool is the comprehensive aircraft and system models that include 1) flight mechanics, 2) aerodynamic forces and moments including nonlinear phenomena and ground effects, 3) ground reactions, 4) engine models, 5) autopilot model including control laws and main logic, and 6) actuators and sensors models, for example, air data inertial reference system, ILS, radio altimeter, specific sensors such as accelerometers and rate-gyros and computers delivering logic for autopilot.

The SAO specification (Spécification Assistée par Ordinateur, which means computer-aided specification: a specific graphical language) of the actual autopilot and flight-control computers are used as inputs to automatically code the autopilot control laws. This leads to a reliable and efficient procedure. To further increase the model accuracy, time delays are taken into account in the simulated computers.

Model Matching with Flight Data

To gain confidence in the simulated responses, it is necessary to compare the computed outputs with the actual flight-test records at various conditions. This matching is necessary for the following needs: 1) model identification and control laws tuning in the development phase, 2) certification to give confidence to air-worthiness authorities in the model from which all of the automatic landing risks are extracted, and 3) inservice incidents analysis and investigations.

Matching can be performed in an open loop (actuator positions recorded in flight as inputs) and in close loop (autopilot targets,

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winds, terrain, and ILS profiles and flight case imposed from the flight). Model update mainly focuses on 1) landing phase, typically for ground-effect identification; 2) nonlinear phenomena (engine dynamics for low thrust level); and 3) flight envelop borders and extreme conditions (maximum turbulence level, engine out case) to allow a fine tuning of control laws.

Ground-Effect Identification

Ground effects are encountered, in general, for altitude above ground level (AGL) lower than the aircraft wing span. They significantly affect the aircraft aerodynamic behavior and, as a result, the handling qualities and performance.[8] Ground effect primarily affects the lift, drag, and pitching moment. For a given slat/flap configuration, the primary effects on the aerodynamics are 1) increase in lift coefficient, 2) increment of pitching moment, and 3) increment of downwash. The change in downwash at the horizontal tail is more pronounced than the pitch-up generated by ground effects on the wing alone. The ground effects affect not only the longitudinal but also the lateral-directional characteristics. Analytical predictions and dedicated wind-tunnel tests provide a priori or preflight models for the ground effect, which is a good starting point for the process of identification from flight data.

The incremental aerodynamic coefficients ΔC_L, ΔC_m, and $\Delta\varepsilon$ (lift, pitching moment, and downwash increments respectively) induced by ground effect are functions of 1) slat/flaps configuration, 2) Mach number, 3) angle of attack, 4) height above ground, 5) flight-path angle, and 6) thrust level through jet interaction.

Calibration of Flow Angles

Accurate knowledge of the flow variables is necessary for precise modeling of ground effects. Angle of attack and calibrated airspeed are obtained from airflow probes. The anemometric and clinometric probes are calibrated in 1) free air and 2) ground effect. In the latter case, computational fluid dynamics (CFD) computations provide a good representation of the phenomenon. Nevertheless, the CFD results have to be validated and adjusted to flight-test (FT) results.

Dedicated flight tests, such as stabilized level flight over the runway (also called tower flyby) are necessary for a good calibration.[9,10] During such tests, a differential global positioning system (DGPS) trajectory is recorded; this information is mandatory to obtain precise AGL and also for determination of wind components as well. Availability of DGPS data resulted in significantly reduced discrepancy in the associated parameters, yielding better consistency from test to test.

Flight Tests

Ground-effect identification starts early in the flight tests campaign because the ground phases are critical and encountered during each takeoff and landing (manual or automatic). Hence, two types of flight tests are carried out: 1) open loop, stabilized level flights in ground effects and manual landings; and 2) autolands in closed loop.

To enable proper analysis/identification, tests at several flight conditions are carried out to cover the entire flight regime: 1) light/medium/heavy weights, 2) forward/medium/aft c.g. positions, and 3) range of angle of attack. Table 1 summarizes the different conditions for a given slat/flap configuration. In the present paper, attention is focused on the landing phase associated with engines on idle thrust.

Table 1 Flight conditions

	Open loop		Closed loop
Parameter	Level flight	Manual landing	Autolands
c.g.	Mid	Forward, mid, aft	Forward, mid, aft
Height, % span	10, 30, 50, 150	From 150 to 0	From 150 to 0
Weight	Mid	Light, mid, heavy	Light, mid, heavy
α, AOA, deg	≈ 5	0 to 8	4 to 8
Slope, deg	0	−3	−3

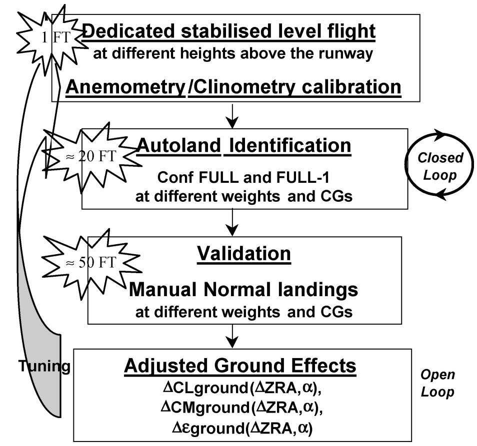

Fig. 1 Schematic of identification process.

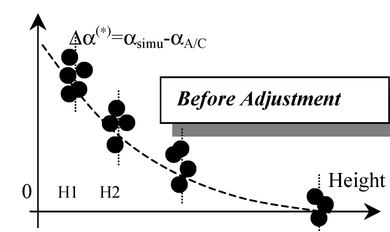

Fig. 2 Angle-of-attack analysis before adjustment.

Identification Process

Figure 1 gives a schematic of the identification process, where the abbreviations FT and RA denote flight test and radio altimeter, respectively.

The approach shown in Fig. 1 needs a significant amount of flight tests to identify the primary influences observed on the aerodynamic coefficients. These specific flight tests for identification purposes are a part of the overall test campaign. They are analyzed with those carried out in the calm air with any autopilot standard. During the model tuning process, the drag coefficient is considered to be of secondary effect and, hence, not adjusted initially. Nevertheless, the final check is done with all adjusted coefficients to make sure that the final objective is achieved. On this basis, proof of match is delivered to support the process of 1) cat III certification (autolands tests)[6] and 2) training simulator approval (level flights, normal landing tests).

Stabilized Level Flights—Open-Loop Tests

The associated tests are mainly the stabilized level flights above the runway and manual landings. The main objective of the stabilized level flights is to validate the aerodynamic ground-effect characteristics at different heights above ground. These tests are carried out in two certified landing configurations, at 1.23Vs1g, for one c.g. condition, and preferably in calm air.

During a stabilized flight phase, knowing the true angle of attack, the simulated angle-of-attack value is adjusted through the aerodynamic coefficient ΔC_L (lift increment induced by ground effects). In the same manner, by setting the elevator deflection to the flight-test values, it is possible to adjust the horizontal trim to the flight-test value through the $\Delta\varepsilon$ (downwash increment induced by ground effect). These test were not sufficient to identify completely the ground effects because they were limited to 1) four heights above runway, 2) single c.g. location, 3) single trim with angle of attack corresponding to 1.23Vs1g and zero path angle ($\gamma = 0$), and 4) scatter of α and γ during tests.

This identification yields only rough tendencies; nevertheless, it is a good starting point for the process just described. As a typical example, the process of adjusting the incremental lift coefficient and the resulting improvement in the angle of attack in the simulation is brought in Figs. 2–4. Specifically, Fig. 2 shows the difference

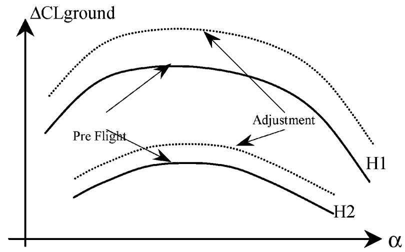

Fig. 3 Lift analysis.

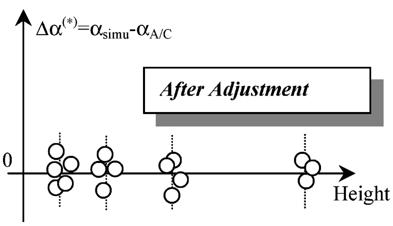

Fig. 4 Angle-of-attack analysis after adjustment.

between the flight measured angle of attack $\alpha_{A/C}$ and that simulated incorporating nontuned model α_{simu}. It is clearly observed that the error is a function of the height above ground.

Based on the preceding analysis of angle of attack, incremental lift caused by ground effect is adjusted at two altitudes. The preflight and adjusted curves are shown in Fig. 3. Having adjusted the lift contributions caused by the ground effect, the simulation now yields the angle of attack that matches well with the flight measured values, as seen from Fig. 4, showing the deviations at all altitudes to be scattered around zero. A similar approach as just described is followed to adjust the downwash to match the horizontal trim.

Closed-Loop and Open-Loop Manual Landings

Autoland tests are landing tests with autopilot in the loop. Autopilot laws include speed and c.g. dependent gains. Autopilot simulations ensure a proper entry in ground-effects region by tracking the glide (equivalently the altitude, which is the more sensitive parameter of ground effect) close to the flight-test values.

Autoland identification is carried out by matching closed-loop simulations using the recorded runway profiles. High fidelity of the complete set of models yields more accurate results because the discrepancy between the flight and simulation for 1) point of impact allows the refinement of precisely the $\Delta C_{\text{Lground}}$ and 2) elevator deflections allow to adjust the $\Delta\varepsilon_{\text{ground}}$. In this case, instead of angle of attack, pitch attitude is matched, which is an input parameter of automatic pilot (difference between both parameters is the slope nearly at -3 deg tracked by autopilot). Furthermore, the accuracy obtained on pitch attitude is better than that obtained on the angle of attack (AOA) provided by the probes.

Besides the open-loop stabilized and closed-loop autoland tests, manual landings were investigated in a statistical sense to smooth out the model adjustments, thereby leading to a model representative of the fleet of aircraft. In the complete process of ground-effects identification, roughly 70% of aerodynamic coefficient adjustment is based on analysis of autolands, the remaining 30% on the stabilized level flights and manual landings. As a typical example, Figs. 5 and 6 show a comparison of the flight measurements for angle of attack and elevator deflection respectively with preflight model and also for model tuned by identification process. Improved correlation of tuned model with flight data is apparent.

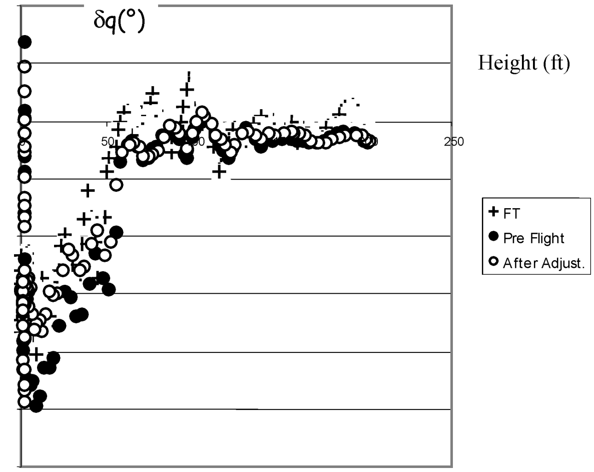

Fig. 5 Comparison of AOA.

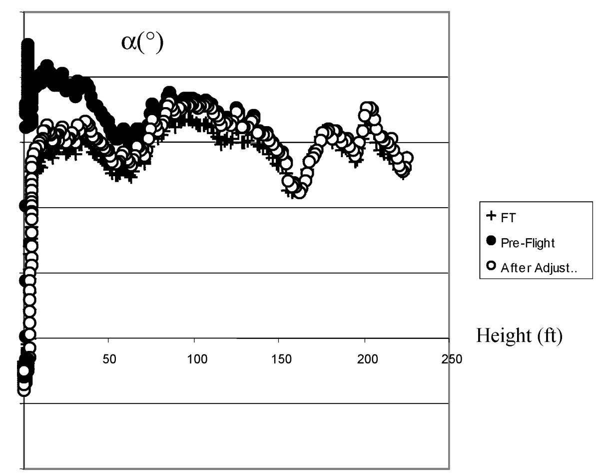

Fig. 6 Comparison elevator deflections.

Applications of the Reference Simulation Models Updated by Identification Process

The updated and flight validated high-fidelity models, resulting from the aforementioned aircraft identification and tuning process, are used: 1) as reference model for simulation, 2) for design of complex aircraft systems such as automatic landing, and 3) to support certification and for training simulators. The scope of such applications is brought out on four examples.

Automatic Landing System Tuning

With the increase of computational power of computers, the role of simulation in the automatic landing tuning process has also increased dramatically. The need of high-fidelity models in the realistic simulation has already been highlighted. As described in the foregoing sections, sophisticated identification techniques combined with DGPS information provided simulation models meeting the high-fidelity and confidence levels.

Since then, the work of automatic pilot design engineer changed fundamentally. Whereas several weeks were necessary in the past to obtain about 10 or 20 test results, today a large number of simulation test results are generated in a few hours. Once the best simulation tuning is achieved, it is automatically coded in an automatic pilot computer and tested in flight.

The experience of recent Airbus aircraft developments showed that the validation coverage of the automatic landing system can be significantly increased through the use of simulation. It has led to reduction of time in such a proportion that the tuning of automatic landing system is now a part of the aircraft initial development program. For instance, in the recent several years all of the new Airbus aircraft models have been delivered to the customers at the entry into service, with the category 3 autoland capability, which was not the case in the past.

Automatic Landing System Certification

The key step in the automatic landing system development is the certification process. The current regulation applicable to this

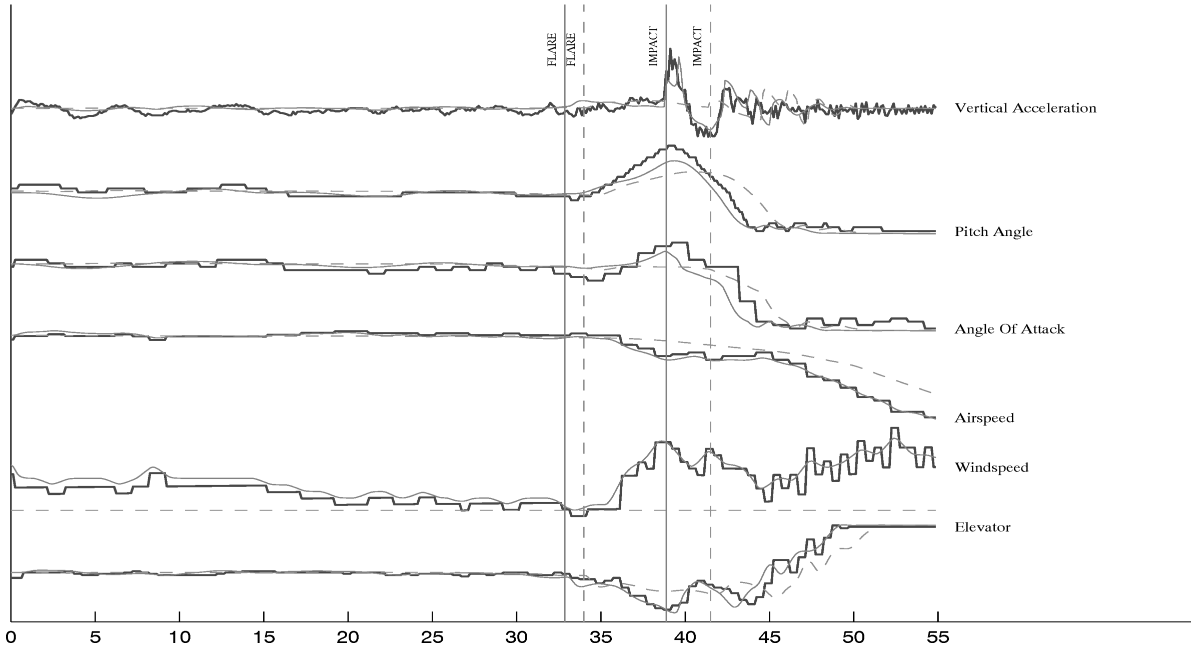

Fig. 7 Analysis of inservice incidence: ——, DFDR measured data; . . . ., simulation with wind; and - - - -, simulation without wind.

system includes several failure cases analysis and performance demonstrations in flight. The principal means to conduct these demonstrations are the flight tests, but European and U.S. regulations (JAR and FAR)[6,7] allow extensive use of simulation. Accordingly, one of the first certification activities is, therefore, to demonstrate to the authorities the validity of the simulation model, which is used at different stages of the certification process.

In addition, the reference aircraft model is also used in the simulator for assessment of the systems failure conditions and of their criticality. Lots of failures cannot be tested in flight for safety reasons, and so, only a very accurate simulation allow assessing the consequences of such failures. Therefore, the high-fidelity simulation directly improves the correctness of the safety assessment process and, in consequence, increases the overall safety level of the aircraft.

Training Simulators

An important part of the crew training is performed on simulators. During these training sessions, pilots are made to face unusual situations involving sometimes the aircraft security. Only high-fidelity simulation permits realistic representation of the situations as close as possible to real situations. To reach this objective, the aircraft simulation model needs to take benefit of the identification results in the whole flight domain.

Analysis of Inservice Incidents

Occasionally, the airlines report events observed in service that are considered as out of the usual average aircraft behavior. These events, called inservice problems, necessitate analysis and explanation by the design engineers. For automatic landing system, in most of the cases these reported events are slight deviations compared to the usual performances, for instance, a landing distance slightly longer or a landing a bit harder than usual. Even though these performance deviations remain far within the certified safe limits, such behaviors have to be explained. Most of the time it is required determine which of the following causes lead to the particular event; either a failure of airborne system or an external disturbance (wind, turbulence) way out of the normal range.

In such an investigation, crew reports and data recorder information are analyzed. This is often sufficient to identify the cause of the event and to provide the airline with an explanation. But sometimes, these data are not enough to analyze unambiguously the incidence or aircraft systems. In those cases, high-fidelity and validated simulation environment is necessary to replay the event and to determine whether the system has failed or not. A replay of one inservice problem, reported during an automatic landing as unusual hard touchdown during autoland, is illustrated in Fig. 7.

Analysis of digital flight data recorder (DFDR) data showed that a tail wind gradient was encountered during the flare. However, just on the basis of these data, it was not straightforward to conclude that wind gradient was the only cause. In the further analysis this event was replayed on a simulator tool at the same flight conditions as the real flight. Wind was estimated from DFDR data and introduced in the simulation. Figure 7 shows the time histories of pertinent variables from measured DFDR data sampled at 1 Hz in continuous lines, the simulated responses neglecting the wind as dashed lines, and those accounting for wind in dotted lines. The flare and impact point in the two simulations with and without wind are marked. These simulations led to the unambiguous conclusion that the cause of this event was the wind perturbation and not the failure of aircraft system. The high level of confidence in the simulation results is based on the fact that the aircraft simulation model incorporates flight-validated database derived applying identification process.

Alleviation of Automatic Landing Certification Process on High Elevation Runways

As already brought out, automatic landing system certification requires performance demonstration at all operational flight conditions. The specific case of runway elevation is of particular importance. The philosophy promoted by Airbus company is briefly elaborated here. During manual landing on high elevation runway, verification of the ground-effect model validity is considered sufficient to prove the validity of the aerodynamic model used in the automatic landing simulation, and thereby avoid the automatic landing tests required to validate the simulation on high elevation runways.

The justification to the proposed approach is as follows: The only part of simulation that potentially needs updating caused by the high elevation runway conditions is the ground-effect model. As already explained, the ground-effect model currently used consists of adjustments for aerodynamic coefficients ($\Delta C_{\text{Lground}}$, $\Delta C_{\text{mground}}$, $\Delta \varepsilon_{\text{ground}}$). On the basis of dedicated wind-tunnel tests, the Mach-number effect is assumed constant. This simplification is acceptable for low Mach numbers (say 0.25 or below), which is the case on low elevation runways for a classical aircraft approach speed. For higher Mach numbers (case of high elevation runways), there is no theoretical analysis that justifies the validity of this simplification.

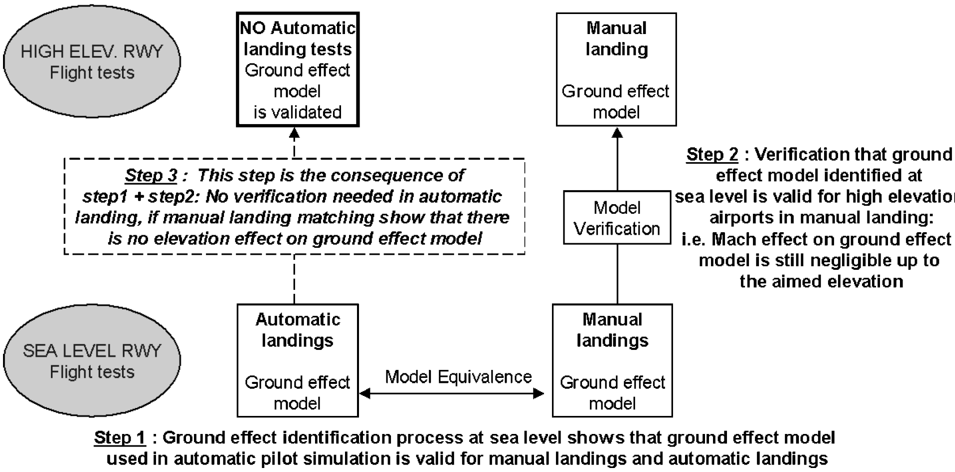

Fig. 8 Schematic of certification process for autoland on high elevation runways.

As a result, validation of the ground-effect model on high elevation runways can be summed up as to validate that the Mach-number effect on the aerodynamic coefficient adjustments is negligible up to the maximum elevation aimed.

The ground-effect model is initially adjusted on a low elevation runway using the identification process already described in the paper. This model is valid for simulation of both manual landing (open loop) and automatic landing (closed loop). To check that the Mach-number effect is still negligible on the model up to a given elevation, it is proposed to perform manual landings and associated calibration tests, on a runway located at that elevation, and to match these tests by the simulation. If the matching gives satisfactory results, this will prove that the Mach-number effect is negligible for this given aircraft up to this elevation. In that case, the ground effect part of the automatic landing simulation is considered to be validated. The method is summed up in the three steps described in Fig. 8.

Conclusions

In the development of automatic landing system, the gains brought by the improvements of aerodynamic and ground-effect models are considerable. Various steps involved in the model adjustment for ground effect are elaborated. It shown that proper model tuning requires stabilized level flights over the runway, autolands, and manual landings. Such model updates and validation from flight data are done applying system identification techniques. The use of DGPS trajectory and increase of computational power has enabled intensive use of the simulation for certification. The high-fidelity simulation, possible through flight-validated and updated models applying system identification techniques, can be considered today as a viable alternative means to the flight tests for quite a few specific demonstrations or verifications. The approach propagated in this paper will very soon be the standard practice for certification method of the automatic landing on high elevation runways.

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