Nonlinear Simulation of Aircraft Terminal Maneuvers Including Gear Dynamics and Ground Effect

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Abstract. Due to ground proximity and limited time to react to possible issues, take-off and landing maneuvers represent the most critical conditions within the envelope of any airplane. In this context, accurate modeling of terminal maneuvers is essential to evaluate performance, identify possible issues, and assess the safety integrity of a design solution. This work focuses on the development of a nonlinear flight simulator capable of handling terminal maneuvers, including the impact of wind and ground effect on the aerodynamic characteristics of the aircraft. The proposed simulator is employed in different landing scenarios including crosswind conditions for evaluating the maximum wing-tip clearance.

Introduction

Terminal maneuvers represent the most critical conditions within an aircraft flight envelope. In the event of unexpected occurrences, pilots are given only a few seconds to assess the situation and respond appropriately, because of ground proximity [1, 2]. For this reason, accurate modeling of take-off, landing, and the associated airborne phases is essential to analyze the aircraft behavior in these conditions and identify potential safety concerns. This work focuses on the development of a nonlinear flight simulator tailored to terminal maneuvers, capable of handling both take-off and landing, as well as all airborne flight conditions. The simulator also accounts for the impact of wind and ground effect on the aerodynamic characteristics of the aircraft.

Although simple simulation methods relying on lumped elements are sufficient for many preliminary aircraft design applications to provide a general understanding of aircraft behavior during take-off and landing [3, 4, 5], a more sophisticated modeling approach is necessary when analyzing realistic terminal maneuvers, especially under windy conditions. Several factors must be considered. First, the airplane may touch down or lift off asymmetrically, such as one leg making contact first, so the kinematics of the aircraft movement must be accurately reproduced. Second, the contact between each leg and the ground requires consideration of the nonlinear dynamics of the landing gear and tires, including their interaction with the ground. Third, airplane aerodynamics are highly complex and must account for the variation in aerodynamic properties due to ground effects, affecting lift, drag, and moment coefficients.

This work focuses on the development of a nonlinear flight simulator tailored to terminal maneuvers, capable of handling both take-off and landing, as well as all airborne flight conditions. This simulator is an evolution of the one described in Ref. [6], utilizing standard rigid-body dynamics equations to model the aircraft motion, with its orientation parameterized using Cardan angles. The rigid-body dynamics is supplemented by the dynamics of the tires and landing gear, along with a specialized function to detect which leg, if any, has made contact with the ground. The aerodynamic angles are calculated while taking into account the presence of wind of generic magnitude and direction.

Additionally, the simulator includes a dedicated tool to model the aircraft aerodynamic characteristics, partially based on Digital Datcom [7], providing steady-state data and stability and

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control derivatives across the entire flight envelope, including the impact of ground effects on these characteristics. Due to certain limitations of the Datcom software, e.g. only one movable surface can be analyzed at a time, the derivation of the aerodynamic model is performed through multiple analyses in a prescribed process, which can also be applied to unusual configurations [8].

The paper is organized according to the following plan. In the section *Methodology*, the simulator will be described putting emphasis on the procedure based on Datcom to estimate the overall aerodynamic characteristic of a given airplane so as to create a large database which considers both longitudinal and lateral directional models and the impact of ground effect on both stability and control derivatives. Some examples of the possible use of the simulator will be reported in the section *Results*. This includes a comparison between landing performed with static aerodynamic model in which stability and control derivatives do not change as the airplane approaches the ground, and an evaluation of minimum wing-tip clearance and maximum lateral gear load during landing as functions of landing speed and crosswind velocity. Finally, section *Conclusions and outlook* concludes the paper by summarizing the main findings and the possible extension of this work.

Methodology

The simulator tailored to terminal maneuvers, which is the focus of this paper, is an evolution of the one described in Ref. [6]. It first relies on the standard rigid-body dynamics equations to model the aircraft motion, while Cardan angles are used for parameterizing the orientation of the airframe with respect to the navigational frame. The aerodynamic angles are calculated while taking into account the presence of wind with a specified magnitude and direction.

The rigid-body dynamics is supplemented by the dynamics of the tires and landing gear, along with a specialized function to detect which leg, if any, has made contact with the ground. In particular, a simplified tricycle landing gear geometry is implemented in which each gear leg consists of a tire and an oleo-pneumatic shock absorber. Tire behavior is rendered through a point-contact model, represented by a linear spring-damper system. The values of the equivalent tire spring and damper characteristics are chosen from literature to yield realistic deformations during simulations. Friction between tires and ground are formulated according to [9], which provides expressions for computing longitudinal and lateral friction coefficients. Braking is also simulated as an additional friction force.

The shock absorbers are modeled using basic physical nonlinear equations linking the elastic force to the stroke and the pressure inside the gas chamber, whereas the dissipative component is rendered through the usual damping arising from flow of the oil through an equivalent orifice. The forces generated at each landing gear contact point are integrated into the aircraft overall equations of motion. The landing gear dynamics is considered only when tire-ground contact is detected.

Additionally, the simulator includes a dedicated tool to model the aircraft aerodynamic characteristics, partially based on Digital Datcom [7], providing steady-state data and stability and control derivatives across the entire flight envelope, including the impact of ground effects on these characteristics.

Due to certain limitations of the Datcom software, and in particular that only one movable surface can be analyzed at a time, the derivation of the aerodynamic model is performed by simulating multiple analyses in a prescribed process.

First, the nominal aircraft is modeled in Datcom including flaps. The outcome of the analysis is the aerodynamic model of the airplane parameterized for different Mach numbers and different flap deflections. The model comprises steady characteristics (e.g. polar and steady moment coefficient) and dynamic stability derivatives.

The same analysis performed at point 1, is repeated including the deflection of the elevator. The outcome of this analysis consists in the variation of the lift $\Delta C_L(\alpha, M)$, drag $\Delta C_D(\alpha, M)$ and moment $\Delta C_{\mathcal{M}}(\alpha, M)$ coefficients entailed by the elevator deflectionδ_E as function of the elevator deflection itself, the angle of attack α and Mach number M.Finally, $\Delta C_L(\alpha, M)$, $\Delta C_D(\alpha, M)$ and $\Delta C_{\mathcal{M}}(\alpha, M)$ should be then added to the polar obtained at point 1.

This analysis considers the ground effect. Since it is possible to analyze only one control surface at a time, the ground effect analysis is done in conjunction with multiple flap deflections, neglecting in this way the mutual impact of ground effect and elevator deflection. Datcom allows for the study of up to 9 deflections and 10 ground heights. Since the ground effect becomes essentially negligible for ground heights greater than the wingspan, the analyzed ground heights, normalized by the wingspan, range from a minimum value of 0.1 to a maximum value of 1. Digital Datcom performs the analysis for every combination of flap deflection and ground height. Additionally, no impact on the lateral-directional stability derivatives is considered.

In the fourth analysis, the ailerons are included in the Datcom model to estimate the aileron-related control derivatives, $C_{\mathcal{L}\delta A}$ and $C_{\mathcal{N}\delta A}$, which are given as functions of the aileron deflection δ_A and Mach, M.

The fifth analysis considers a model of the isolated fuselage to estimate the increment in the related drag caused by side-slip angle β. Since Digital Datcom does not support analyses varying with β, the approach is to rotate the fuselage by 90 degrees around the x-body axis. This way, when Datcom performs its standard analysis varying α on the rotated fuselage, it effectively analyzes the fuselage aerodynamic characteristics as a function of β.

This step considers the estimation of the control derivatives with respect to the rudder deflection and the increase in the drag entailed by the gears. Both tasks are accomplished using the approach described in [10]. The simulator is implemented in Matlab, and, for the discontinuity management, the model from Ref. [11] was used: as several discontinuous events occur during landings (contact with ground, rebounds, shock absorber motion), the simulation had to be segmented in between the events to avoid numerical problems due to integration of stiff systems.

Results

To demonstrate the capabilities of the simulator, a model of the Ryan Navion (a single-engine, propeller driven, four-seat aircraft) is considered. The digital Datcom was employed to characterize the aerodynamic modeling of the airplane as described in the Methodology section.

In the first scenario, we considered landing in calm air without the flare maneuver. In particular, the airplane was trimmed at a descending angle equal to 1 deg and the controls (deflection of control surfaces and throttle) are maintained fixed throughout the entire simulation. In order to show the importance to have a good characterization of the ground effect, two cases were simulated: one including the variation of the ground effect as function of the distance between the airplane center of gravity and the ground, and the other considering constant aerodynamic coefficients no matter the ground proximity.

Fig.1 shows the output of these simulations, respectively in terms of the airplane trajectory and flight angles as functions of the horizontal distance. The plots also compare two cases: one where the ground effect is considered (solid lines) and one where it is not (dashed lines).

In the considered scenario, due to the ground effect, resulting from the combined modification of the aerodynamics of the wing and tail, the aerodynamic pitch moment increases in magnitude while the airplane descends, causing a tendency to pitch the nose downward. This increase in pitching moment depends on many factors, including the location of the center of gravity and wing aerodynamic center, and is airplane-specific. This behavior is not new, as it was also observed in a paper by O'Leary on a de Havilland DH.106 Comet [12].

From the obtained outputs, although the approach angle is 1 deg, the airplane touches the ground at nearly 3 deg. Notably, this result would not have been obtained if the impact of the ground effect on the moment coefficient had not been considered.

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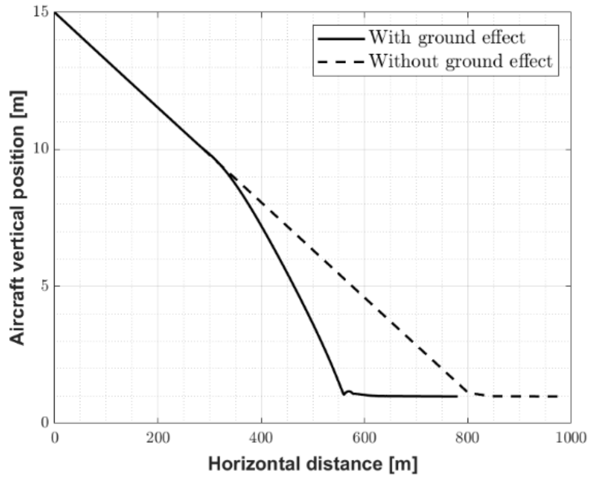

Figure 1: Example of the effect of ground effect on a landing simulation in calm air. Left plot: aircraft trajectory. Right plot: pitch angle (green line), climb angle (red line) and angle of attack (blue line). Solid lines: including ground effect; dashed lines: without ground effect.

In a second scenario, a crosswind is included in the simulations, as well as a dedicated automated control that models pilot's actions. Specifically, the pilot performs the flare before touching the terrain and, once the nose leg has touched the terrain, it also steers the nose wheel to align the trajectory of the airplane with the runway. A crosswind of 8 m/s blows from the left of the airplane, perpendicular to the runway direction. The landing simulation begins with the flapped aircraft in a trimmed configuration, with the nose aligned with the runway, yielding a sideslip approach, where the heading angle matches the flight path angle. Due to the crosswind, both the sideslip and roll angles are non-zero and touchdown occurs asymmetrically, with the left leg touching the ground first, followed by the right leg and, finally, by the nose leg. Fig. 2 shows the trajectory of the aircraft center of gravity during a landing with crosswind of 8 m/s coming from the left of the airplane. In the same plot, it is also possible to visualize the airplane trajectory on the runway after touchdown that follows the runway direction thanks to the nose wheel steering.

The same analysis was repeated multiple times for different values for the approach speed and the crosswind velocity in order to evaluate the impact of these quantities on minimum wing tip clearance. The maximum crosswind considered is 14 m/s, a value that is 50% higher than the maximum crosswind demonstrated in field for Navion aircraft. Fig. 4 shows the minimum wing tip clearance as a function of both approach and crosswind speed. It is possible to show that the worst case, referring to the approach speed equal to 45 m/s and crosswind equal to 15 m/s is associated with a minimum clearance of about 0.7 m. This value, although lower than the clearance for null crosswind, is still significantly positive, demonstrating the landing is still safe even in the presence of crosswind with severity significantly higher than that tested for certification.

Conclusions

A flight dynamics simulator has been developed, coupled with landing gear dynamics, capable of simulating any flight phase, including terminal maneuvers. The aerodynamic characteristics of the airplane are nonlinear and are obtained through a dedicated set of Datcom analyses to generate the aerodynamic dataset which also accounts for ground effect. The use of nonlinear aerodynamics, unlike linearized models, avoids introducing additional errors related to the deviation from the equilibrium point around which the linear model is built. A terminal phase control system has been also designed, to model the presence of the pilot acting on all control surfaces, throttle and nose wheel steer. The tool is effective in simulating terminal maneuvers also in presence of crosswind, without introducing significant simplifications to the dynamics and aerodynamics modeling. A

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parametric study has been also performed to quantify the impact of crosswind on the minimum wingtip clearance to verify possible wingtip strikes. The analyses show that the reference aircraft can safely land even at crosswind speeds 50% higher than the maximum one demonstrated in field, without issues related to wingtip strikes.

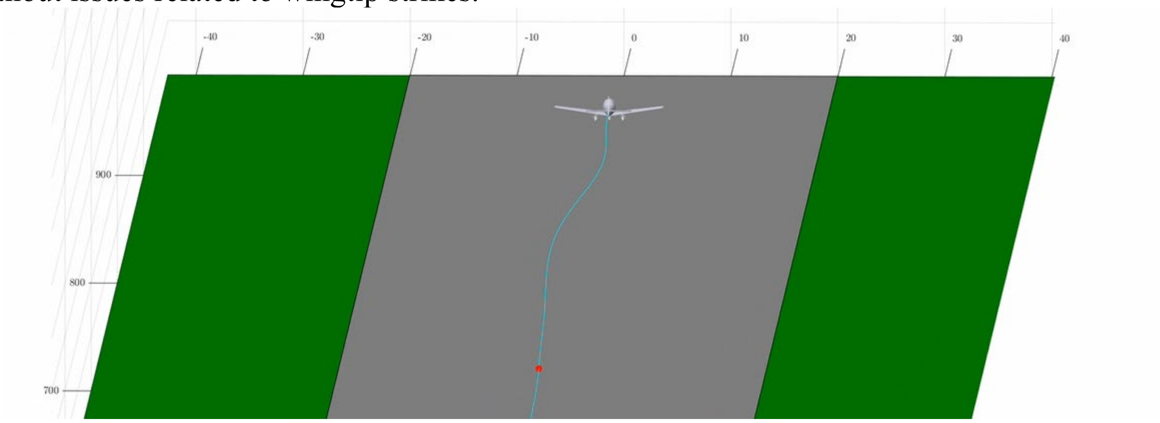

Figure 2: Airplane trajectory during landing with crosswind. Red mark: touchdown point.

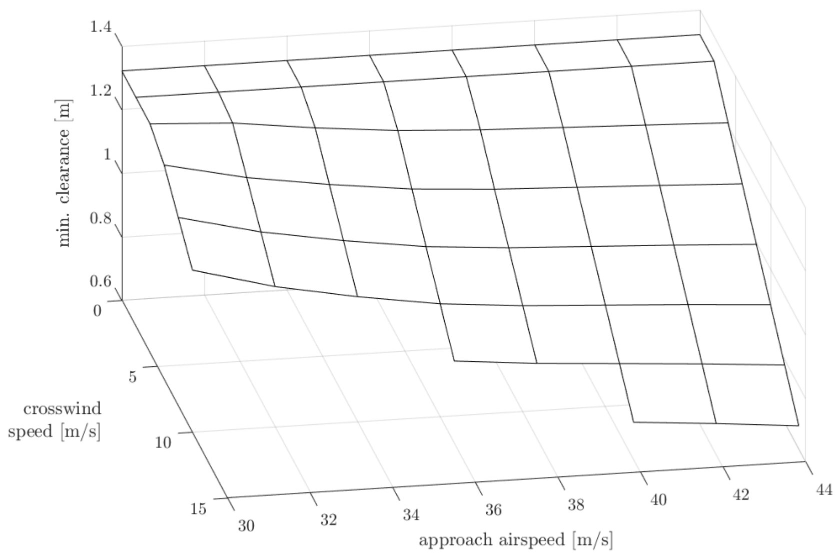

Figure 3: Minimum wingtip clearance as function of approach and crosswind speed

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