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On-ground aircraft control design using a parameter-varying anti-windup approach

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ABSTRACT

As an original alternative to dynamic inversion techniques, a non-standard anti-windup control strategy is developed in this paper in order to improve the on-ground control system of a civilian aircraft. Using a linear fractional representation (LFR) of the aircraft in combination with an original approximation of the nonlinear ground forces by saturation-type nonlinearities, the proposed design method delivers low-order and robust controllers, which are automatically adapted to the runway state and to the aircraft longitudinal velocity. The efficiency of the design scheme is assessed by several nonlinear simulations.

1. Introduction

Fly-by-wire systems are now commonly used on-board transport aircraft. They allow the automation of many parts of the flight, including the highly nonlinear landing phase. This automation significantly reduces the piloting workload that traditionally required the full attention of pilots, such as navigation tasks, weather watch, air traffic communications and on-board activities monitoring. This is permitted by the fly-by-wire laws that control the airplane and ensure that it follows some precise orders. In addition, some flight-domain protections contribute to enhancing the safety of flights by preventing from entering abnormal conditions. Aircraft manufacturers work in close collaboration with academics in order to integrate some modern control techniques to their process, making today fly-by-wire control laws highly reliable, robust and efficient. In the past years, enhanced functionalities such as turbulence or gust alleviation have thus been introduced, allowing increased comfort in flight, but also decreased structural loads on the airframes.

On the other hand, aircraft on-ground control remains very limited and mainly consists of heading and velocity control once aligned on the runway before take-off or after touch-down. It is performed without explicit control of the pilot and the dedicated control laws are quite simple compared to those developed for the flight phases: they do not offer the same protections of the normal operating envelope, and robustness to external disturbances or variation in the runway state is not ensured. Moreover, apart for keeping the aircraft on the runway, all turns and maneuvers on ground are directly performed by the pilots using manual open-loop control. This difference between in-flight and on-ground control can be explained easily. Aerodynamics and their impact on handling qualities have been extensively studied in the past. But the on-ground motion is more complex due to the coupling between aerodynamics and friction forces between the wheels and the ground, the latter being highly nonlinear and depending on many external parameters. Of course, right after touchdown, the aerodynamic effects are dominating, while on the taxiway the main concern is ground forces. Nevertheless, the coupling between the two is high during the acceleration and deceleration phases. Moreover, the effects of wind or gusts are amplified by the aerodynamic characteristics of the aircraft, and they significantly impact the ground forces and the motion along the runway or the taxiway.

Air transport has experienced several runway overruns in the past years. A first benefit of using an autopilot to automate the on-ground motion would thus be to improve the safety during airport operations whatever the visibility, rain, wind or gust. But there is also an economic benefit. Indeed, the longitudinal distances between aircraft currently need to be increased in bad weather conditions. And managing the on-ground traffic requires additional safety margins in case of fog. In this context, the automation of the on-ground motion appears as a prerequisite to

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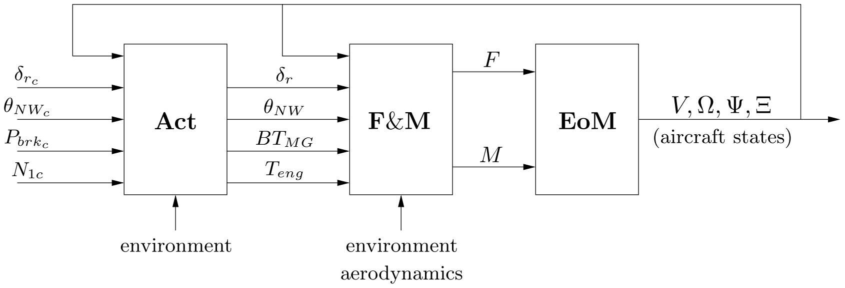

Fig. 1. General architecture of the initial nonlinear model.

a more autonomous on-ground traffic and to increased airports traffic capabilities. These requirements are pushing for developing enhanced on-ground control functionalities. The first step consists in developing robust ground-by-wire control laws, so as to pilot the lateral load factor N_y or the yaw rate r for the lateral motion, and the longitudinal load factor N_x or the ground velocity V_x for the longitudinal motion. The second step is then to develop autonomous navigation, such as runway exit at the right speed while minimizing the occupation time, or autonomous motion along the taxiways towards the selected gate for instance. These last tasks can be performed by computing the right orders to send to the ground-by-wire control laws. The most challenging aspect today, which is investigated in this paper, is thus the first step: being able to provide a safe, robust and reliable on-ground control of an airplane in the highly nonlinear and fast varying context of the on-ground motion.

A preliminary solution based on a nonlinear (NL) dynamic inversion technique was proposed in [10] to control the lateral motion of an on-ground aircraft. More precisely, it was shown in this paper that linear methods could not be directly applied for this specific control application. An alternative solution is proposed here, which consists in reducing the highly nonlinear interactions between the tyres and the ground to saturation-type nonlinearities. The resulting control issue thus falls within the scope of anti-windup techniques. In this context, a dynamic anti-windup design method based on modified sector conditions [13] is proposed to optimize a newly introduced performance level for saturated systems [8]. The extension to parameter-varying systems is also highlighted. Interestingly, the problem is shown to be convex for the considered application. As a result, the anti-windup gains are easily computed. Moreover, it is shown that the saturation levels, which depend on the runway state, can be identified on-line, and that the resulting estimator can be written as an LFR. This enables a clever adaptation of the performance levels. The present contribution should thus be read as a non-standard application of anti-windup control, which is here an original alternative to dynamic inversion.

The paper is organized as follows. A high-fidelity nonlinear on-ground aircraft model developed in an industrial context is succinctly described in Section 2 and a simplified design-oriented LFR is derived in Section 3. The proposed control strategy is stated in Section 4, while Section 5 is devoted to the presentation of some new results regarding anti-windup design and to the way they can be extended to handle parameter-varying plants. Section 6 then details both the design process on the simplified model and the controller implementation on the full nonlinear plant. Several simulations are performed, which demonstrate the significant improvements induced by the anti-windup compensator. Concluding remarks are presented in Section 7, which also provides directions for future works.

2. Description of the high-fidelity on-ground aircraft model

2.1. General architecture

The open-loop nonlinear model presented in this section describes the on-ground dynamics of an Airbus transport aircraft with two engines. It is representative of the aircraft behavior from touchdown to complete stop and can be represented by three main blocks of differential equations, as shown in Fig. 1.

The **EoM** block contains the equations of motion and is generic for all aircraft (on-ground and airborne). Its inputs are the total forces F and moments M and its outputs are the twelve standard aircraft degrees of freedom, namely the linear and angular positions ($\varPsi$ and $\varXi$) and velocities (V and $\varOmega$). As an example, the evolution of $V = [V_x\ V_y\ V_z]^T$ and $\varOmega = [p\ q\ r]^T$ is described by:

$$\begin{bmatrix} \dot{V} \\ \dot{\varOmega} \end{bmatrix} = \begin{bmatrix} \frac{F}{m} - \varOmega \wedge V \\ I^{-1}(M - \varOmega \wedge (I.\varOmega)) \end{bmatrix} \tag{1}$$

where I is the inertia matrix and m the aircraft mass.

The main forces $F = [F_x\ F_y\ F_z]^T$ and moments $M = [M_x\ M_y\ M_z]^T$ acting on the aircraft are modeled in the **F&M** block and correspond to the aerodynamic effects, the gravity, the engines thrust and the ground forces. They depend on several aerodynamic and environmental data, but also on the positions of the actuators (rudder deflection δ_r, nose wheel angular position θ_{NW}, braking torque at main landing gear BT_{MG} and engine thrust T_{eng}). The aerodynamic coefficients C_x, C_y and C_z are modeled by neural networks. But the most specific and important contribution comes from the ground forces F_{ground}, which are induced by the interactions (wheel slip, rolling drag, braking forces) between the nose wheel (NW) and main landing gear (MG) tyres and the ground. Their computation is quite complex because they are highly nonlinear functions of the local sideslip angles β_{NW} and β_{MG}, but also of the vertical load F_z, the runway state (dry, wet or icy) and the aircraft longitudinal velocity V_x. A macroscopic nonlinear model is used which combines various elements from [2,3].

The **Act** block contains the actuators models. It is composed of three nonlinear subsystems associated to the nose wheel steering system, the braking system and the engines.

2.2. Need for a simplified model

The nonlinear model presented in Section 2.1 is described by differential equations. It is not directly compatible with the anti-windup design tools developed in Section 5, which require the considered plant to be written as an LFR.[1] A first method is to convert it using the nonlinear symbolic LFT modeling approach

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[1] Basically, building an LFR consists in transforming the initial system into a time-invariant plant $M(s)$ in feedback loop with a block diagonal operator Δ, which contains all the nonlinearities, the varying parameters and the uncertainties of the system. A good introduction to LFT modeling can be found in [17].