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A novel structure design and control strategy for an aircraft active sidestick

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***Abstract*— This paper is concerned with a new design of an aircraft active sidestick based on Permanent Magnet Synchronous Machine (PMSM) and proposes an innovative robust control strategy based on an adaptive optimal sliding mode controller.**

Indeed, such an application requires high performance specifications which impose many constraints (torque, torques ripples, temperature). Here, a new design for the sidestick actuator is provided with a specific structure: a double airgap rotating one adapted to the considered process. Then, an optimization is performed to enhance the set of specifications of the PMSM w.r.t the aeronautical application.

Also, a new adaptive optimal robust control for the designed actuator is provided based on the linear quadratic approach combined with the sliding mode control method. Then, an adaptive disturbances rejection is performed with the proposed strategy.

Due to the considered design of the actuator ($1/12$ of a complete PMSM), a position control is achieved based on the LQR-Sliding mode approach to meet the required performances and to manage the plant parameter variation and load disturbances. Also, a varying parameter is used to adapt "on-line" the considered control to the varying level of disturbance that affect the system.

First simulation results of the considered strategy applied to the newly designed actuator (compared to other strategies) proves the efficiency of the proposed solution for position control of the actuator and robustness considering load disturbances.

***Keywords*: Aircraft sidestick, actuator design, structure optimisation, linear varying parameter, linear quadratic control, sliding mode control.**

I. INTRODUCTION

During decades, the evolution of aircrafts and aeronautical vehicles has been related to the development of process that allows to manage their behaviour depending on several parameters (size, weight, aeronautical surfaces, performance...). One of the moste important mechanisms is the Fly-by-wire control that allows to handle the aircrafts flight attitude. Conventionally, a mechanical passive sidestick system is used for the fly-by-wire.

Usually, two passive sidesticks are available in the cockpit, to create force feedback depending on the displacement angle of the stick compared to the natural resting position: on the left side for the pilot and for the right side for the copilot.

Nowadays, this kind of sidestick is not convenient anymore due to the evolution of the size of aircrafts (see [1]). To overcome this issue, a new type of sidestick called "active sidestick" that uses motors, electronics and high bandwidth closed loop control system to control these oversized aircrafts with less pilot effort while providing grip feel of spring return, breakout forces and soft stops (in [2] and [3]). Indeed, there is two main type of control systems: electro-hydraulic and electric systems. While the electro-hydraulic ones allow to adapt the aircraft behaviour to flight envelope through a variable stifness, the electric systems provide excellent characteristics regarding force feed back (with high bandwidth allowing to change the stiffness and adapt the aircraft behaviour) and also new functions that ensure haptic feedback.

Recently, it has been proven that the haptic sensations of the pilot can be enhanced thanks to the active sidestick technology. Indeed, its advantage is that the grip feel characteristics can be used/configured depending on the pilot inertia. In addition, other features such as two-sidesticks coupled operation (for the pilot/copilot) can be easily implemented using feedback signals instead of links connecting the two sticks as in [4]. This technology has also some attractive characteristics that makes it viable in aircraft applications as:

1) Small and low weight.
2) Reliable with high integrity in the aircraft environment.
3) Dynamically reprogrammable to adapt to several configurations.

Then, the linear state feedback control seems to be very attractive to control this kind of actuators since it has the full flexibility of shaping the dynamics of the closed loops system to meet the desired specifications (see [5]). Considering these specifications, the optimal *LQR* control method is an easy way to decide the demand control law to satisfy the requirements. Based on the state-space model, a relative Riccati equation is first solved and an optimal feedback gain, will lead to optimal results evaluating from the defined performance index. But, one important issue is once the external disturbance and/or parameter uncertainty exists, the desired responses may not be obtained (lack of robustness). A robust control strategy is proposed to handle the disturbances and the parameter uncertainties. The developed strategy is a two step control approach: the first one is the LQR method used to shape the actuator dynamics and meet the requirement of the performance index, called the "reaching phase". The second one is the sliding mode method which ensures the robustness in the sliding phase of the

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variable structure control. Then, robustness is kept in the optimal control scheme for the considered motor. In addition, a varying parameter is used to adapt "online" the robust control to the level of the disturbances in linear varying parameter strategy.
This paper is organised as follows: section *I* is devoted to introduce the aspects of design and control of the new proposed actuator. In section *II*, requirements specification for the structural design of the actuators is presented. Section *III* presents the new control strategy proposed for the position control of the considered actuators. Section *IV* presents the simulation results in different scenarios that validates the developed control strategy for the designed actuator. Conclusions and some future works that we are investigating are presented in last section.

II. Specification requirements and structure design

A. Requirements

One important step before beginning any design procedure is to comply with the set of specifications defined by the considered application (dimensions, forces, strokes, speed, temperature and force ripples),as in [6] and [7]. The aeronautical application requires to have two actuators on each one of the pitch and roll axes (redundancy), implemented in parallel and embedded in a $(175*150*60\ mm)$ box. The grip middle point distance d_{gmp} is the distance between the pivot and the point where the force F_p is applied by the pilot as in Fig. 1. The maximum torque to be developed is:

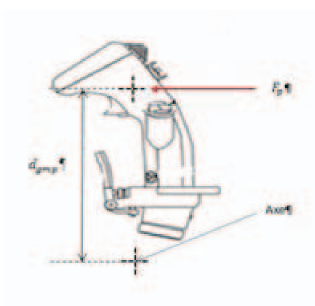

Fig. 1. Grip middle point distance

$$T_p = F_p * d_{gmp} = 3.2(Nm) \tag{1}$$

B. Presentation of the developed structure

The actuator is a rotating synchronous permanent magnet machine with two airgaps as in Fig.2. The stator in iron is surrounded by the coils which are also supplied by three-phase sinusoidal current ([8]). The inner and outer rotors are fixed by a plate and are composed of two iron yokes and magnets arranged in **Halbach array** in Fig. 3.
The variable of displacement for the rotating machine is denoted X (in radian). X_R is the variable that describes the rotor and X_S the one describing the stator. The position of the rotor compared to the stator is given by:

$$S = \theta_r + \theta_{rs} = \theta_r + \Omega * t \tag{2}$$

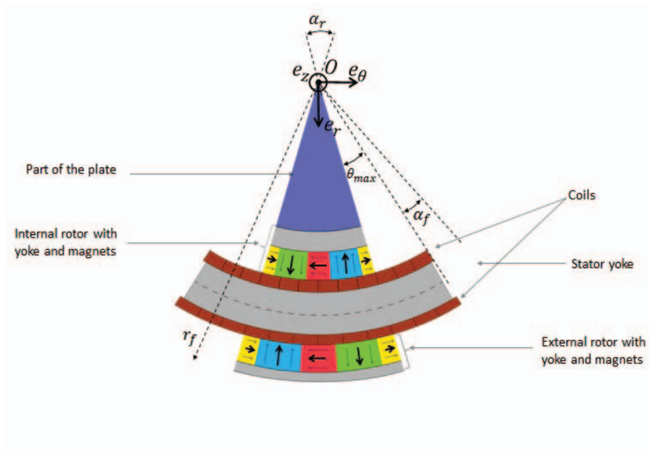

Fig. 2. Representation of the rotative actuator coordinates

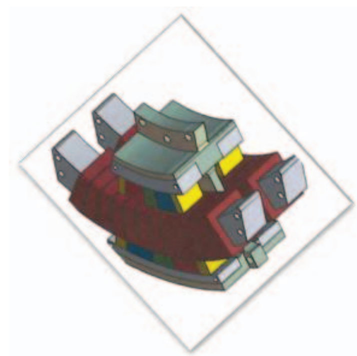

Fig. 3. Rotating actuator

where, Ω: is the rotative velocity.

Remark 2.1:
- The machine is composed of two airgaps, and can be seen as two machines separated by the black dotted line. The upper one is called internal machine and below the external one. The total developed torque provided by this machine is the sum of each one given by this parts.
- Magnets arranged following an **Hallbach array**: a combination between radial and tangential polarizations. This pattern allows to concentrate the magnetic flux inside the airgap in order to increase the torque (see Fig. 4)

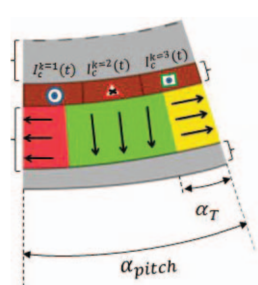

Fig. 4. Representation of Hallbach array

C. Optimization of the actuator design

First, the total force (resp. torque) developed by the each coil of the actuator is obtained by calculating the average of laplace force over a coil area ([6]):

$$T_L^k(t) = \frac{1}{Scoil} \iint_{scoil} \int_z B_y(\theta_s, Y, t).I^k(\theta_s, t).dz.dS \quad (3)$$

Total torque for the rotating actuators, considering 3-phase sinusoidal current are:

$$T_m(t) = 2p \sum_{k=1}^{3} T_k^L \quad (4)$$

where p is the number of pairs of pole, $k = 1,2,3$.
Once these equation established, an optimization specifications procedure has to be performed in order to fit into the specific set of specification due to the very strict aeronautical application (dimensional and heating constraints). The main objective for this actuator is to develop a high torque in a small volume. For this sake, a multi-objective function is used for the optimization, as follows:

$$\begin{cases} min f(x), \\ g_i(x) \leq 0, \forall i \in 1,...,n_g \\ h_j(x) = 0, \forall j \in 1,...,n_h \end{cases} \quad (5)$$

where f is the objective function to minimize under the g and h constraints. x is the fixed variable and n_g and n_h are respectively the number of inequalities and equalities constraints.
The objective function is given as follows:

$$f(x)(t) = \sum_i \gamma_i \frac{f_i(x)}{||f_i||} \quad (6)$$

with

$$\sum_i \gamma_i = 1 \quad (7)$$

where γ_i is the weight given to each objective f_i. Indeed, the following objective functions are considered:

$$f_1 = T_m \quad (8)$$

$$f_2 = \eta = \frac{P_{em}}{P_{em} + P_{joule}} \quad (9)$$

where η is the efficiency of the actuators. $P_{em} = C_m.\gamma$ is the electromagnetic power and P_{joule} is the Joule losses. Here, the eddy losses are not considered because the supply frequency is low ($< 10Hz$) du to the maximal rotating speed imposed by the specifications ($100°/s$).

TABLE I
OPTIMIZED PARAMETERS OF THE DESIGNED ACTUATOR.

Parameters	New designed Rotating machine
Torques (Nm)	3.17
Mass (kg)	0.95
Torque per unit of mass	3.65

Based on these optimization results (see Table. I), it can be clearly seen that the torque generated by the rotating actuator meets the requirements specified previously in (1). Based on this study, and in the following, the rotating actuator structure is maintained and used in the control strategies synthesis.

III. ROBUST OPTIMAL SLIDING MODE CONTROL DESIGN STRATEGY

The proposed control strategy is developed to meet the performance requirements and handle the issues described above. Since the considered actuator is a part of the wole cylindrical PMSM, the rotational motion of this actuators is in the rang $[15^{\circ}, 15°]$. A postion control of the rotative displacement of this actuator to generate the required torque must be achieved. The control strategy contains two parts: LQR control to shape the actuator dynamics ([9]) and variable structure control based on the Sliding Mode ([10]) for the robustness purposes. Also, the level of robustness to the disturbances is adapted "online" using a varying parameter based on the variation of the system inertia (main disturbance induced by the pilot inertia). This strategy is summarized in Fig. 5.

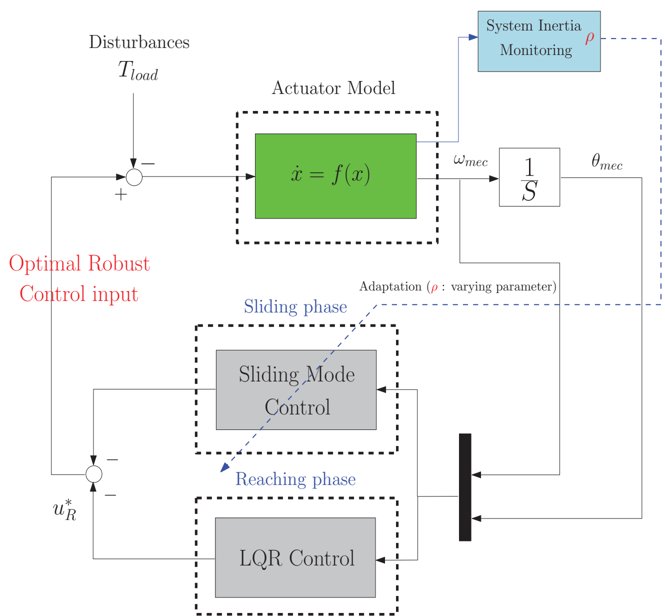

Fig. 5. Robust optimal actuator position control strategy.

A. Actuators model control-oriented

The considered PMSM actuators can be described by the following equations describing its rotation behaviour:

$$\begin{cases} v_d = L_d \frac{d}{dt} i_d + R_s i_d - \omega_s \phi_q \\ v_q = L_q \frac{d}{dt} i_q + R_s i_q - \omega_s \phi_d \end{cases} \quad (10)$$

and

$$\begin{cases} \phi_q = L_q i_q \\ \phi_d = L_d i_d + \phi_m \ (avec \ \phi_m = L_m I_{mf}) \end{cases} \quad (11)$$

where, v_d, v_q are the $d,q-axes$ stator voltages, i_d, i_q are the $d,q-axes$ stator currents, L_d and L_q are $d,q-axes$

stator inductances, λ_q and λ_d are $d,q-axes$ stator flux linkages. Also, R_s and ω_s are the stator resistance and electric pulse while L_m and I_{mf} are the mutual inductance and the equivalent $d-axis$ magnetizing current.
The corresponding developed electromagnetic torque T_{elec} is given as follows:

$$T_{elec} = \frac{3}{2}p[L_m I_{mf} i_q + (L_d - L_q) i_q] \tag{12}$$

where p the number of pole pairs.
Then, the corresponding electromechanical equations are:

$$\begin{aligned} & J_{mec}\frac{d\omega_{mec}}{dt} + B_{mec}\omega_{mec} = T_{elec} - T_{load} \\ & \frac{d\theta_{mec}}{dt} = \omega_{mec} \end{aligned} \tag{13}$$

where θ_{mec} and ω_{mec} are the mechanical position and velocity of the rotor. J_{mec} and B_{mec} are the moment of inertia and the damping coefficient respectively. The electrical frequency (inverter frequency) ω_s is related to the rotor velocity through $\omega_s = p\omega_{mec}$.

Remark 3.1:
- PMSM control is based on the control of field orientation since the magnetic flux is in relation with rotor position.
- T_{elec} is proportional to the controlled current i_q. The current i_d is fixed by the controller at null value.
- J_{mec} represents the moment of inertia created by both the sidestick and the motor, and then T_{load} represents the disturbances induced by the pilot handling of the sidestick.

B. Robust control design

The proposed control synthesis scheme is based on shaping the motor dynamics through the introduction of a performance index and *LQR* feedback gain stabilization. Then, a robust variable structure control based on sliding mode will conserve this performances in non nominal conditions. Also, an adaptation of the robustness level is provided using a varying parameter in an LPV context ([11]).

This control design is based on the state space representation of the PMSM. Based on the previously described dynamical equations, the motor model can be described as follows:

$$\underbrace{\begin{bmatrix} \dot{\theta}_{mec} \\ \dot{\omega}_{mec} \end{bmatrix}}_{\dot{x}} = \underbrace{\begin{bmatrix} 0 & 1 \\ 0 & -\frac{B_{mec}}{J_{mec}} \end{bmatrix}}_{A} \begin{bmatrix} \theta_{mec} \\ \omega_{mec} \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ \frac{1}{J_{mec}} \end{bmatrix}}_{B} T_{elec} + \underbrace{\begin{bmatrix} 0 \\ \frac{1}{J_{mec}} \end{bmatrix}}_{disturbance} T_{load} \tag{14}$$

Remark 3.2: One of the main advantage of using the **Hallbach** polarization is to shape the magnetic field flux to avoid the saturation on the motor borders ([12]). Thus, only isolated points of saturation could appear while using the motor at maximum torque. This saturations are considered as disturbances of the nominal behaviour of the motor and will be managed by the proposed robust control structure.
The aim of this control is to track a desired position of the PSMS based on the state space representation.

$$\dot{x} = Ax + Bu \tag{15}$$

First, an LQR optimal control is used to find an optimal input u^*, that minimizes the performance index:

$$J = \int_0^\infty (x^T Q x + u^T R u) dt \tag{16}$$

where **R** is positive definite matrix, and **Q** is nonnegative definite matrix.
The optimal control input u^* for the considered system is obtained by first computing the nonnegative solution $\bar{P}$ of the following Riccati equation:

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \tag{17}$$

Then, the optimal feedback to be applied to achieve the performance objective of the position tracking is the following:

$$u^* = R^{-1}B^T \bar{P} x \tag{18}$$

Then:

$$K = R^{-1}B^T \bar{P} \tag{19}$$

This *LQR* optimal control is used to shape the dynamics of the motor to meet the required performance in the nominal case, but it may not be sufficient in case of disturbances or parameters uncertainties. Indeed, for more realistic conditions, the model of the actuator is as follows:

$$\dot{x} = (A + \Delta A)x + (B + \Delta B)u + d \tag{20}$$

where, ΔA and ΔB are the system parameters uncertainties and d is the external disturbances.
Thus, the uncertain model in (20) can be simplified by gathering the uncertainties and the external disturbance in one general disturbance input to the nominal behaviour of the system, as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -a_1(1+\Delta_1)x_1 + b(1+\Delta_2)x_2 \end{cases} \tag{21}$$

Then, this system (21) is rewritten as follows:

$$\dot{x} = Ax + Bu + pert \tag{22}$$

where

$$pert = \Delta_1 Ax + \Delta_2 Bu + d \tag{23}$$

The previously developed LQR optimal control (19) can not handle this disturbances. It is the raison why the following robust sliding mode control complementary strategy is introduced ([13]). A switching function $s(t)$ for the sliding mode control position base on the LQR feedback defined in (19):

$$s(t) = C^T x(t) - C^T A_c \int_0^t x(\tau) d\tau = 0 \tag{24}$$

where A_c is the closed loop dynamical matrix obtained using the LQR control in (19), C^T is chosen to fulfill the following condition: $C^T B \neq 0$, so it can meet the requirement of the sliding mode definition and simplify (24). A simple solution is $C^T = [0 \ 1/J_m]$. Based on the system in (20), $\sigma(t) = 0$ during all the process control. The new control input u_R^* that allows to keep the nominal behaviour of the system under the perturbed conditions is given as follows:

$$\begin{aligned} u_R^* &= u^* - \rho sign(s(t)) \\ &= -K^T x - \rho sign(s(t)) \end{aligned} \quad (25)$$

The sign function is quite rough since it is defined as:

$$sign(s(t)) = \begin{cases} +1 \ if \ s(t) > 0 \\ -1 \ if \ s(t) < 0 \end{cases} \quad (26)$$

Then to have smoother function and simplify the sliding optimal control, the following robust control input is considered:

$$u_R^* = -K^T x - \rho \frac{s(t)}{|s(t)+\delta|} \quad (27)$$

where $\delta << 1$.
ρ is the varying parameter that adapt the level of robustness of the considered control strategy "on-line" to the total perturbation, as follows:

$$|\frac{pert}{B_{mec}}| \leq \rho \quad (28)$$

Several academical studies have shown that the pilot inertia is the main disturbances source that affect the behaviour of the active sidestick, mainly, changing the system inertia. Thus, the adaptation of the robustness of proposed controller is scheduled by the following varying parameter ρ, based on the variation of the system inertia:

$$\rho = \frac{|J - J_{nominal}|}{|J_{nominal}|} \leq 1 \quad (29)$$

where, J: is the system global inertia (affected by the pilot), $J_{nominal}$: the designed actuator inertia.

Remark 3.3: Using a varying parameter to adapt the level of rejection of the proposed robust control leads to a polytopic representation of two vertices of the control. Thus, the global dynamical LPV controller can be easily written in a convex polynomial combination of local controllers on the vertices of a polytop formed by the higher and lower bound of the variation interval of the varying parameter ρ.
Then, it is established that for any optimal *LQR* feedback (see (19)), the system has a switching surface (σ) on which the states slides.

Remark 3.4: Let us recall that the sliding mode $\sigma(t) = 0$ exists if the switching surface of the considered system satisfies the following condition:

$$s(t)\dot{s} < 0 \quad (30)$$

Robustness proof.
The previously proposed robust control for the actuator position is based on the sliding mode strategy. The mathematical robustness proof is the following:

$$s(t)\dot{s} = s(t)(C^T \dot{x}(t) - C^T A_c x(t)) \quad (31)$$

$$s(t)\dot{s} = s(t)[\frac{1}{J_m}\dot{x}_2 + (\frac{1}{J_m}[k_1 x_1 + (1 + \frac{k_2}{J_m})])] \quad (32)$$

Then by considering the uncertainties in the model, it leads to the following expression

$$\begin{aligned} s(t)\dot{s} = s(t)[\frac{1}{J_m}(-\frac{B_m}{(J_m+\Delta J_m)}x_2 + \frac{1}{(J_m+\Delta J_m)}u_R^*) + \\ (\frac{1}{J_m}[k_1 x_1 + (1 + \frac{k_2}{J_m})x_2])] \end{aligned} \quad (33)$$

By replacing u_R^* as in Eq. 27, the following inequality is obtained,

$$s(t)\dot{s} \leq s(t)[\frac{p_{pert}}{B} - \rho sign(s(t))] \leq 0 \quad (34)$$

Which proves that the control existence and stabilization condition of the sliding mode for the proposed strategy is fulfilled.

IV. Simulation

To test the efficiency of the the proposed control strategy, the following scenarios are considered. First, the objective is to control the position of the motor in **nominal** conditions for the considered angles range of variation (-15° to $+15^{\circ}$). A comparison between only the *LQ* controller and the proposed sliding mode combined *LQ* control is presented to evaluate the performances. The following simulations are for a position tracking of $0.5235 rad$ ($30°$). Fig. 6 shows the

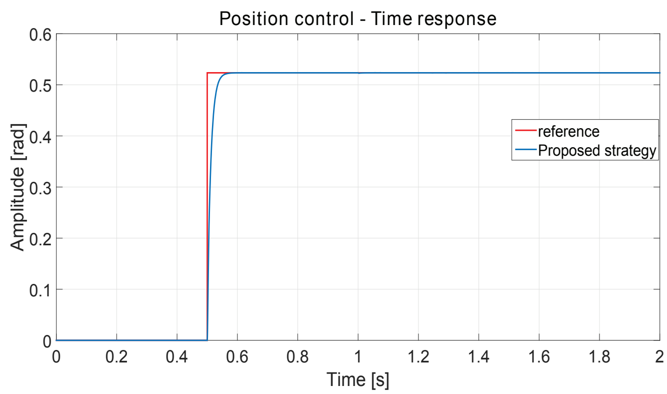

Fig. 6. Position control.

postion of the actuator in nominal conditions. The control is good for both classical LQR and the proposed strategy because this scenario concerns only the "reaching phase" and the two approaches use the same optimal gain K. The proposed control strategy has a time response of $t = 0.05s$ which copes with the considered application requirements.
It is understandable that the two control strategies have the same trajectories in the disturbance-free part of the scenario since they have the same dominant poles.
The second scenario concerns the position control of the PMSM in disturbed conditions (uncertainties and external disturbances). Since this actuator is designed for a sidestick pilot application, a small angles are to be applied and in two directions. In this scenario, a sine wave with an amplitude $3°$ angle applied to the newly designed sidestick actuator. Then, at $t = 1$ the system is subject to a significant disturbance. Fig. 7 shows the dynamical behaviour of the actuator for a position control in disturbed condition. The simulation compares between a classical LQR and the new optimal sliding mode (variable structure) control. It can be seen that the classical LQR control can not handle the disturbance (step signal in the simulation). Indeed, a close look to Fig. 8 shows that the *LQR* control approach is optimal in the "reaching phase" but it can not handle the disturbances.

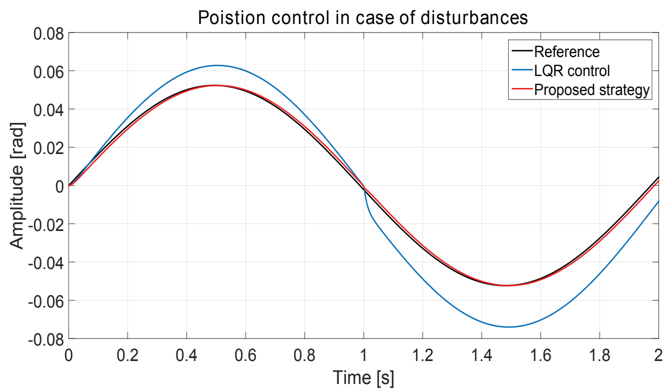

Fig. 7. Position control: disturbed conditions.

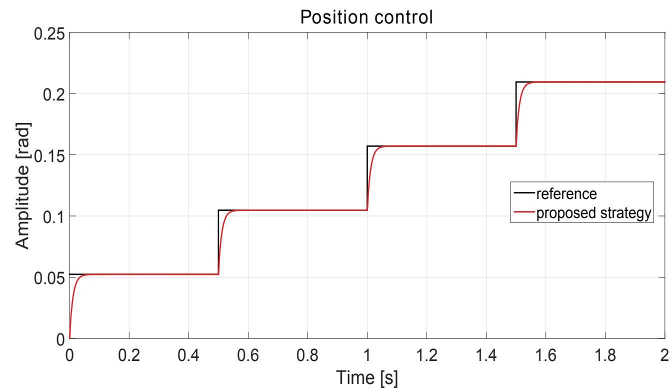

Fig. 9. Consecutive reference tracking

Thus, It can be clearly seen that the LQR control can not ensure the position tracking of the reference signal in these conditions. Conversely, the proposed optimal sliding mode

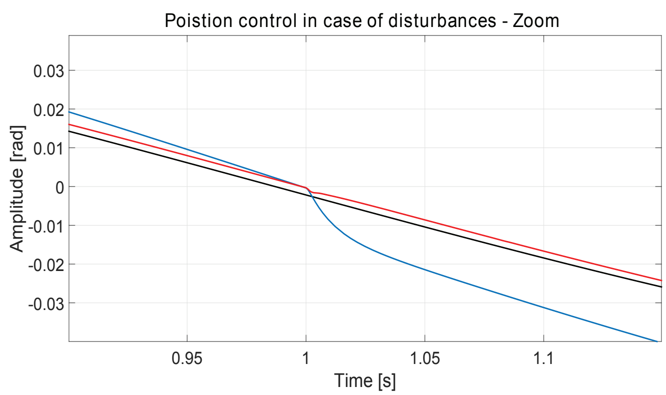

Fig. 8. Position control: disturbed conditions-Zoom.

strategy is very robust to the disturbances. The sliding control allows to keep the performance objective and to reject all the disturbance instantaneously by stabilizing the states of the system in the "sliding phase". Then, the new proposed strategy (by combining the LQR in the reaching phase and the sliding mode in disturbed conditions) ensures a robust optimal control from the beginning of the process.
The *RMS* (Root Mean Square value) of the position tracking error signals allows compare these strategies. For the proposed robust control strategy, the *RMS*of the tracking error is of 2.8% while for the LQR the *RMS* of the error is of 23%. This proves the efficiency of the proposed strategy.
The next scenario simulate the behaviour of the pilot who can apply consecutive actions on the sidestick to correct the aircraft position as in Fig. 9. It can be clearly seen that the proposed strategy can handle such situation that can occurs due to the pilot behaviour.

V. Conclusions and Future Work

In this paper, the design of a new sidestick electromagnetic actuator for aircraft application have been presented. Then, an innovative adaptive optimal robust control based on LQR sliding mode strategy that allows an enhanced position control, regarding the aeronautical application requirements, even in disturbed conditions.
Simulation results using the designing parameters and comparison with other optimal control strategies proves the efficiency of the described approach for the considered application.
The next step is already scheduled and will be the implementation of this control strategy as soon as the actuator is ready (now in manufacturing phase).

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