

# An Aerodynamic Load for an Electrohydraulic Actuator: Advanced Modelling and Implementation Using Electric Actuators

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## ABSTRACT

This paper presents a proposed methodology of the emulation and the implementation of an aerodynamic load applied to a control surface linked to an electrohydraulic actuator (EHA) used in the primary flight control. An advanced multiphysics model based on bond graph and analytical models of the multiphysics system is developed and a co-simulation using Simulink/AMESim (advanced modeling environment simulation) with a position control is carried out. In the emulation, a platform of two electric machines is used. A permanent magnet synchronous machine (PMSM) with P-salient pole emulates the same machine of the EHA while the pump, jack, control gear and the control surface (elevator) submitted to the aerodynamic resistive torque are emulated by a DC machine. The control laws to implement simultaneously are torque control for the DC machine and velocity control for the PMSM where the velocity set point is provided by the jack position controller. The resistive torque set point is estimated from an aerodynamic model while the angular velocity set point is provided by a position controller where the control surface (elevator) position is estimated by the same model. Choosing an aircraft velocity and an altitude, a control surface position (elevator) set point is deduced and the implemented control laws are validated on the experimental platform. On the other hand the implemented simulator on the experimental platform will be used to study different scenarios of normal or/and abnormal operations in order to test reliability and safety of the EHA supply during flight.

**Keywords:** aerodynamic load, control surface, advanced modeling, co-simulation, emulation, implementation, experimental validation.

## 1. INTRODUCTION

The upcoming “more electric” aircrafts will involve simpler, cheaper and lighter power generation and distribution architectures (typically two electric circuits and two hydraulic circuits). To achieve this goal, “Power-by-Wire” actuation has been developed for years in the directions of electrohydrostatic actuators (EHA’s). Being well suited to primary flight control, they will be used on commercial aircrafts as backup actuation, allowing the cancellation of one central hydraulic circuit [1].

Figure 1 illustrates the main components of the EHA used in the primary flight control of an aircraft such as Airbus 380.

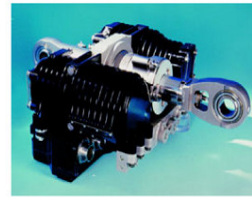


Figure 1: EHA for primary flight control

In the conception of the EHA used in the primary flight, different technologies are used. Figure 2 shows the main multiphysics components which contains the EHA:

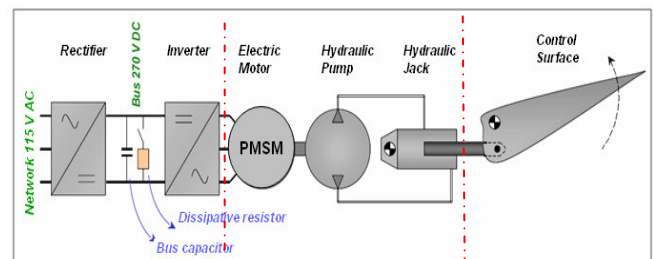


Figure 2: Multiphysics elements of the EHA linked to the power supply and the control surface

A permanent magnet synchronous machine coupled mechanically to a variable flow rate pump which feeds a hydraulic jack in order to adjust, via a control gear, the angular position of the control surface. The measurements of the hydraulic jack position and the motor-pump velocity are realized by two sensors integrated in the system.

The power supply of the PMSM is carried out by a bidirectional inverter linked to a rectifier which provides the continuous bus voltage;  $E = 270V$ .

Also a resistor load is used for the dissipation of the electric energy when the angular position variation of the control surface is negative [2].

The control strategy used for the EHA is a multiloop control design (figure 2) which, for a jack position set point (equivalent to an angular position of the control surface), a set point velocity is provided to the velocity loop. Using the autopilot control strategy in the dq plan of the PMSM, the set point current of  $i_{sd}$  is chosen equal to zero while the set point of  $i_{sq}$  is provided by the velocity controller. The generated pulse width

signals vary the abc stator voltages. However the pump flow rate is modified until the jack position set point is reached.

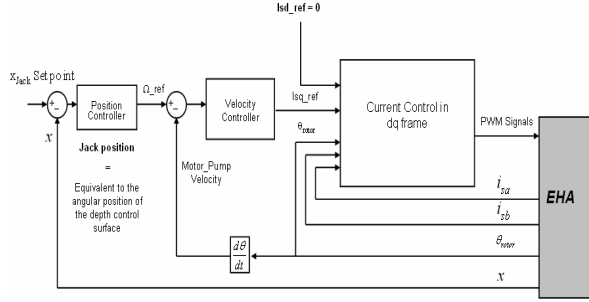


Figure 3: EHA Multiloop control

## 2. MULTIPHYSICS MODELING

In the modeling of the electrohydraulic actuator coupled to the control surface which is submitted to the resistive aerodynamic torque, two approaches are used:

1. Analytic models for the permanent magnet synchronous machine in the dq frame associated to the inverter with a PWM modulation control and, the aerodynamic resistive torque.
2. Bond-graph models for the hydraulic components; the pump, pipes, accumulators, pressure limiter and the hydraulic jack with anchorage compliance [2, 3] and the control surface linked to the hydraulic jack by a control gear where the transmission compliances are taken into account [2].

### 2.1 Analytic modeling

#### 2.1.1 PMSM model in dq frame

In the modeling of the PMSM with p-silent pole an analytical model in dq frame using Park transformation is given by the following equations:

$$V_{sd} = R_a \cdot i_{sd} + L_d \frac{di_{sd}}{dt} - p\Omega L_q i_{sq} \quad (1)$$

$$V_{sq} = R_a \cdot i_{sq} + L_q \frac{di_{sq}}{dt} + p\Omega L_d i_{sd} + p \cdot k_m \Omega \quad (2)$$

$$C_{em} = p \cdot (L_d - L_q) i_{sd} i_{sq} + p \cdot k_m i_{sq} \quad (3)$$

$$C_{em} - C_r = J \frac{d\Omega}{dt} \quad (4)$$

where:

- $R_a$ : winding resistor
- $L_d$ : d axis inductance
- $L_q$ : q axis inductance
- $p$ : number of poles pair
- $k_m$ : back emf coefficient
- $J$ : rotor inertia  $kg \cdot m^2$
- $C_r$ : pump resistive torque

The variables,  $V_{sd}$ ,  $V_{sq}$  and  $i_{sd}$ ,  $i_{sq}$  are voltages and currents in dq frame.  $C_{em}$  and  $\zeta$  are PMSM electromagnetic torque and angular velocity.

### 2.1.2 Voltage Inverter

In the modeling of the bidirectional inverter, the semiconductor switches are considered as ideal. Figure 3 illustrates the link between the arm inverters and the PMSM noted MS. The stator phase voltages  $V_{an}$ ,  $V_{bn}$  and  $V_{cn}$  are deduced in terms of the PWM signals as follows:

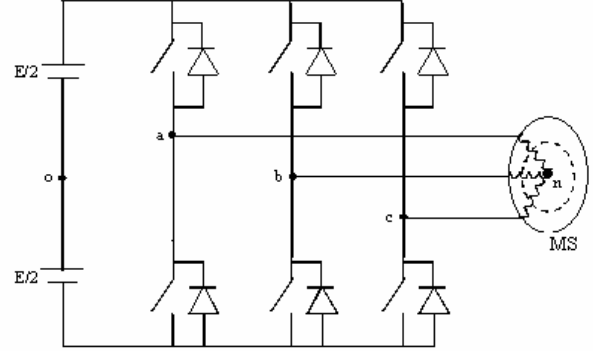


Figure 4: Bidirectional voltage inverter

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{E}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} K_a \\ K_b \\ K_c \end{bmatrix} \quad (5)$$

E: Continuous bus voltage

### 2.1.2 Control strategy

In the control of the EHA, three cascade control loops are designed; position, velocity and current loops (figure 3). The current loops are designed in the dq frame using the synchronous machine model given in § 2.1.1:

Equations (1) and (2) can be written as:

$$V_{sd} = V_{sd1} - e_{sd} \quad (6)$$

$$V_{sq} = V_{sq1} - e_{sq} \quad (7)$$

In these equations,  $V_{sd1}$  and  $V_{sq1}$  are considered as the control signals provided by the current controllers while  $e_{sd}$  and  $e_{sq}$  are considered as the link terms. These terms are deduced by identification using equation (1) and (2):

$$V_{sd1} = R_a \cdot i_{sd} + L_d \frac{di_{sd}}{dt} \quad (8)$$

$$V_{sq1} = R_a \cdot i_{sq} + L_q \frac{di_{sq}}{dt} \quad (9)$$

$$e_{sd} = p\Omega L_q i_{sq} \quad (10)$$

$$e_{sq} = -(-p\Omega L_d i_{sd} - p \cdot k_m \Omega) \quad (11)$$

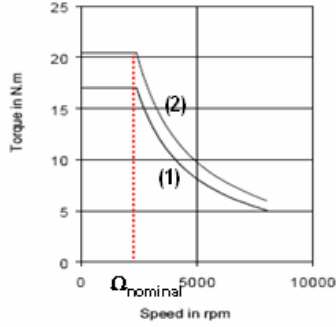
Using placement pole method, two PI current controllers are designed from equation (8) and (9).

The link terms  $e_{sd}$  and  $e_{sq}$  are also integrated in the current loops in order to control separately the currents  $i_{sd}$  and  $i_{sq}$ .

Also two current set points are chosen. According to the control principle where the torque machine is constant until the nominal angular velocity (figure 5), Isd set point is imposed equal to zero while Isq set point is deduced from the torque set point supposing, in the case of the PMSM with p-salient pole Ld is almost equal to Lq thus the term  $p \cdot (L_d - L_q) i_{sd} i_{sq}$  of equation (3) is neglected and we get:

$$I_{sq\_ref} = \frac{C_{em\_ref}}{p \cdot k_m} \quad (12)$$

$$I_{sd\_ref} = 0 \quad (13)$$



(1): steady regime, (2): instantaneous regime

Figure 5: static characteristics torque-velocity

The PI velocity controller is also designed on the basis of the mechanical constant time of the same electric machine. Using the measured PMSM velocity and the velocity set point provided by the hydraulic jack position controller, the velocity control loop provides the appropriate torque set point. The last one is deduced from the measured jack position and a chosen set point.

### 2.1.3 Aerodynamic load

The aerodynamic forces applied to the control surface (elevator) during flight are shown in figure 6.

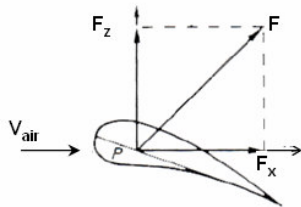


Figure 6: Aerodynamics forces

The drag noted  $F_z$  is the vertical force which opposes the gravity force and is perpendicular to the relative aircraft velocity direction.

$$F_z = \frac{1}{2} \rho V_{aircraft}^2 \cdot S \cdot C_x \quad (14)$$

$$F_x = \frac{1}{2} \rho V_{aircraft}^2 \cdot S \cdot C_z \quad (15)$$

The lift noted  $F_x$  is the horizontal force which corresponds to the aircraft friction forces in the air. This force is in the opposite of the aircraft velocity:

$$F_x = \frac{1}{2} \rho V_{aircraft}^2 \cdot S \cdot C_x \quad (16)$$

S is the elevator surface

$\rho$  is the air density which depends on the aircraft altitude Z:

$$\rho(Z) = \rho(0) \frac{20000 - Z}{20000 + Z} \quad (17)$$

$\rho(0)$  is the air density at the ground. Equation (17) is valid until an aircraft altitude of 10000m.

According to lifting line theory of Prandtl,  $C_z$  and  $C_x$  are respectively the drag and lift coefficients which depend on the angle of attack  $\nu$  (the incidence), and the wing aspect ratio  $\lambda$ . The last one depends also on the wingspan L and the wing twist  $C_0$  of the elevator.

$$C_z = \frac{2\pi\theta\lambda}{2 + \lambda}, \quad C_x = \frac{C_z^2}{\pi \cdot \lambda} \quad \text{and} \quad \lambda = \frac{L^2}{S} \quad \text{with} \quad S = L \cdot C_0;$$

S is the elevator surface considered as rectangle.

From the drag and the lift, the resultant force (figure 6) is deduced as follows:

$$F = \sqrt{F_z^2 + F_x^2} = \frac{1}{2} \rho \cdot V_{aircraft}^2 \cdot S \cdot \sqrt{C_z^2 + C_x^2} \quad (18)$$

According to the linear aerodynamic theory, the resultant force is applied at 25% of the wing twist  $C_0$  in relation to the leading edge of the elevator. The aerodynamic torque is estimated as follows:

$$C_{aerodynamic} = 0.25 \cdot C_0 \cdot \frac{1}{2} \rho \cdot S \cdot V_{aircraft}^2 \cdot \sqrt{C_z^2 + C_x^2} \quad (19)$$

Finally, the elevator is submitted to the estimated aerodynamic resistive torque which depends simultaneously on the aircraft velocity and altitude and the elevator incidence  $\nu$ . Figure 7 illustrates the evolution of the estimated aerodynamic torque for two altitudes;  $Z=0.5\text{km}$  and  $Z=10\text{km}$ . Indeed for the range limits of the incidence  $\nu$ , the aerodynamic torque is more important at low altitude than at high altitude whatever the aircraft velocity maybe.

Also for the same altitude, the aerodynamic torque is more important when the incidence is increasing. Indeed this is, for example, the case when the aircraft is taking off.

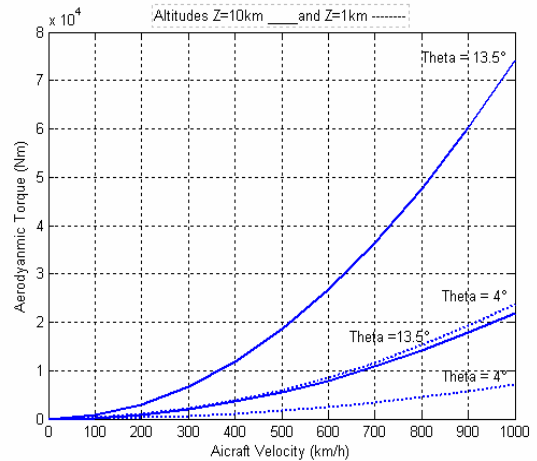


Figure 7: Torque-aircraft velocity characteristics

## 2.2 Bond Graph Modeling

The modeling of the EHA components and the control surface is based on the AMESim libraries. In each library, all the components are conceived on the basis of elementary bond graph models where the causality principle is applied. The main advantage of these libraries is the flexibility of the multiphysics modeling of systems coupling different technical areas. Indeed no need to develop analytical models for physical components [1].

### 2.2.1 EHA components

Using the hydraulic library of AMESim, the modeling of the pump, pipes and the jack is given as follows:

The model pump (figure 8) is a pump with a variable flow rate where internal and external leakages are replaced by pressure drops. Flow rate is computed from the shaft speed and pump displacement while the torque is computed from the pressure variation at the pump.

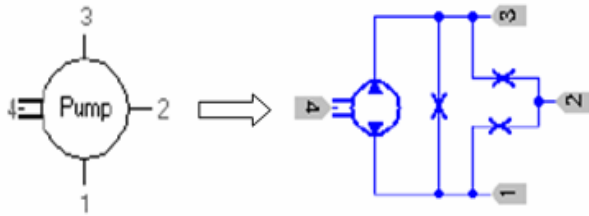


Figure 8: Pump model

- (1): Output/input pump
- (2): Hydraulic feed
- (3): Input/output pump
- (4): Velocity input

The hydraulic block describes anti cavitation function (check valves and accumulator) flow distribution (electrovalve) and pressure relief valves (figure 9).

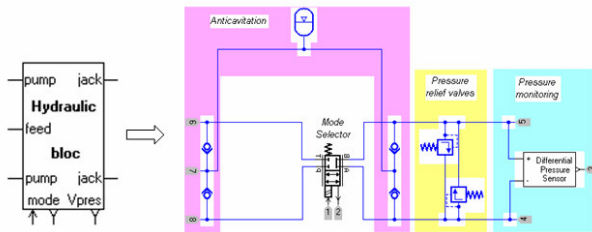


Figure 9: Hydraulic block

- (1): Control signal: (1) Active and (-1) Damping
- (2): No link
- (3): Output differential pressure sensor
- (4): Link between the relief valve and Chamber 2
- (5): Link between the relief valve and Chamber 1
- (6): Link between the pump (3) and the electro valve (T)
- (7): Link between the pump (2) and the accumulator
- (8): Link between the pump (1) and the electro valve (q)

The actuation is composed of a jack with a moving body (piston and envelope inertia are taken into account). This jack (figure 10) is designed from elementary elements of the mechanical and hydraulic libraries. The body and envelop masses are  $M_1$  and  $M$ . The measured piston displacement is the resultant of the envelope and body motions. Two chambers are connected taking into account the jack drop pressures. Forces are computed from pressure exerted on jack and anchorage stiffness to the flap.

Note that the existing jack in the hydraulic library of AMESim can be used but in the EHA, the used hydraulic jack is specific for this application and the proposed model is complete when comparing to the existing one.

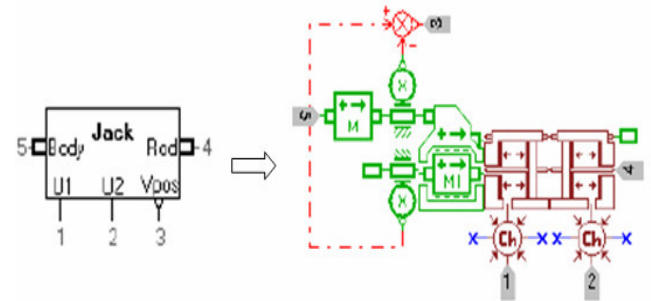


Figure 10: Hydraulic jack model

- (1): Chamber 1 input/output
- (2): Chamber 2 input/out
- (3): Jack position sensor
- (4): a link to the mechanical arm
- (5): a link to the fixation point

The anchorage and transmission compliances [4] are replaced by the association of a spring-damper. Figure 11 illustrates the link of the jack to the control gear and the fixation point.

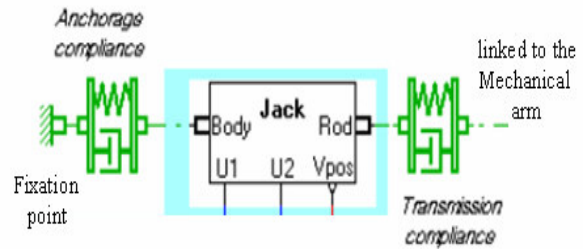


Figure 11: Jack links

### 2.2.2 Control surface (elevator)

The control surface linked to the EHA is the elevator which controls the pitch or the up and down movement of the aircraft. It's located on the trailing edge of the horizontal tail assembly and is controlled by the forward and backward movement of the joystick. Pulling the joystick back moves the elevator up causing the aircraft nose to point up. Similarly, pushing the joystick forward will move the elevator down and pitch the nose down.

In the EHA, the hydraulic jack piston is linked to the elevator by a control gear (figure 2) which translates the linear motion of the piston to a rotational motion on the elevator and the reverse. In the modeling of the mechanical load seen by the piston, an inertia with frictions and a mechanical arm are chosen from the

mechanical library of AMESim. Also an angular position sensor is integrated. Figure 12 shows the mechanical load model with the aerodynamic resistive torque input.

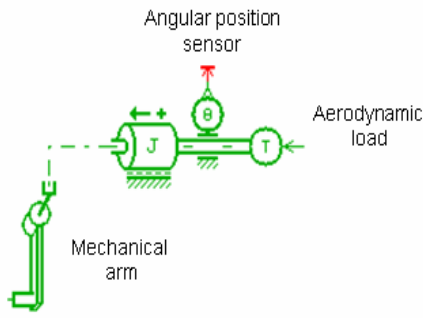


Figure 12: Control surface model

Finally the EHA model is the association of the different physical blocks of AMESim models given by figures 4, 5, 6 and 7 and the PMSM model in dq frame implemented in Matlab/Simulink. Also, the model of the control gear given in figure 12 is connected via the transmission compliance to the jack piston. The aerodynamic resistive torque applied to the control surface is provided by an aerodynamic model implemented in Matlab/Simulink taking into account the velocity and altitude of aircraft. On the other hand an interface bloc is created in AMESim allowing the on-line exchange of variables between AMESim and Simulink models. Figure 13 illustrates the AMESim model of the hydraulic part, the load and the interface block.

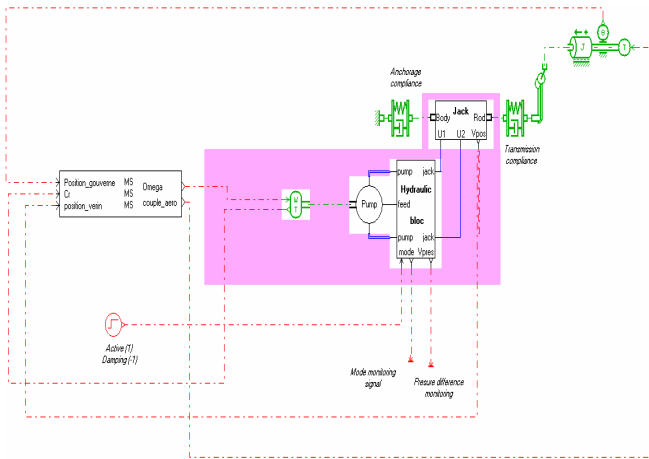


Figure 13: AMESim model of the EHA and the load

In the interface block created in AMESim (figure 9), the input/output variables are defined as follows:

1. The variables to send to Simulink are the angular position of the control surface, the Jack position and the pump resistive torque.
2. The variables to send to AMESim model are the PMSM velocity and the aerodynamic resistive torque.

In Simulink, the PMSM, the power supply (voltage inverter with PWM control), the aerodynamic model and the EHA cascade control are implemented as shown in figure 14. The

AMESim s-function corresponds to the AMESim model of figure 13.

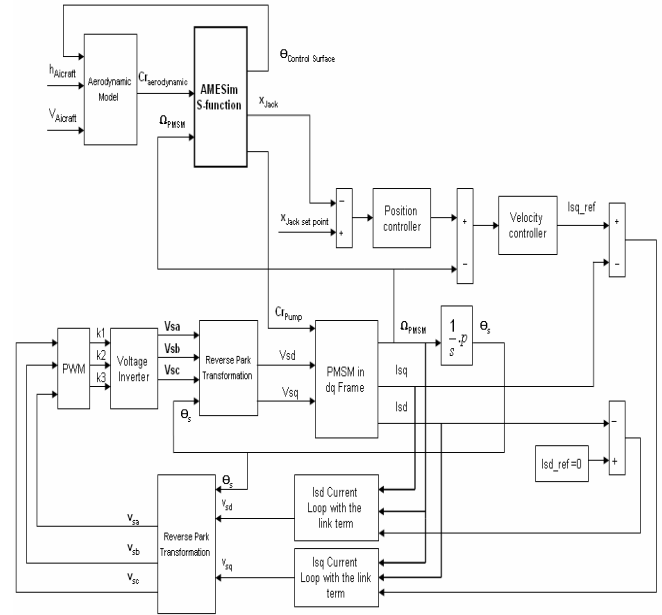


Figure 14: Simulink model

### 3. IMPLEMENTATION AND SIMULATION

Figure 15 illustrates the EHA simulator with the aerodynamic load and the exchanged variables between AMESim and Simulink models.

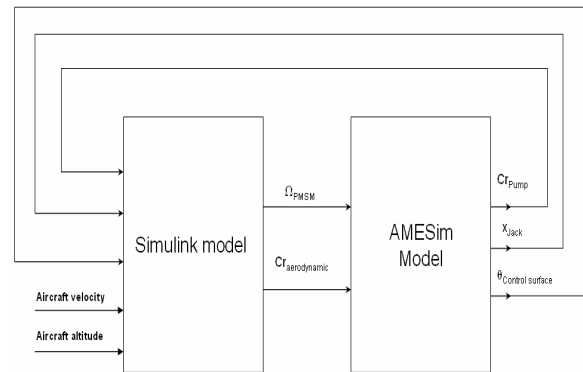


Figure 15: EHA & Aerodynamic load Simulator

The operation point to choose for simulation is defined by aircraft velocity and altitude and the elevator position (equivalent to a jack position). These variables are defined by: The aircraft velocity range: [0-800] km/h, the aircraft altitude range: [0-11] km and the elevator position: [4 - 13.5]°.

Choosing an altitude of 5000 m and an aircraft velocity of 500 km/h, figures 16 and 17 gives the evolution of the hydraulic jack position and the elevator position for two position set points. Indeed the steady state is reached for the two set points.

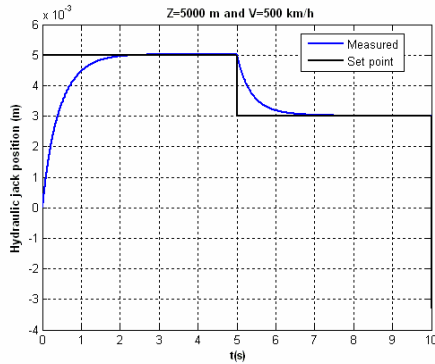


Figure 16: Evolution of the hydraulic jack position

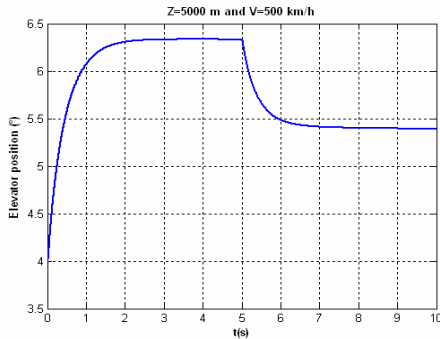


Figure 17: Evolution of the elevator position

Also, the steady state is reached for all the other variables velocity in figure 18, torques in figure 19, stator currents in figure 20 and pressures in the two chambers of the hydraulic jack given in figure 21.

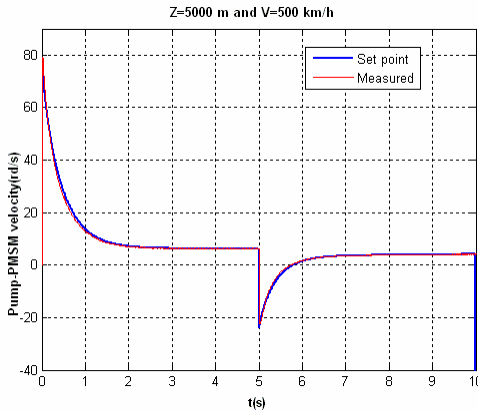


Figure 18: Evolution of the pump-machine velocity

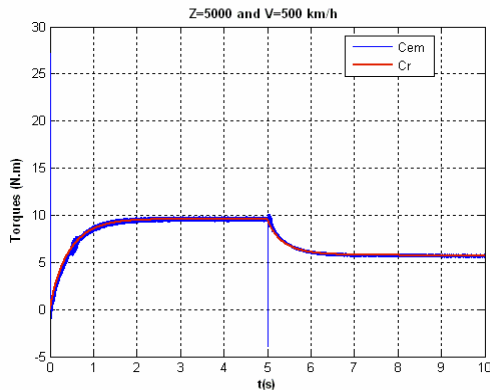


Figure 19: Evolution of the machine and pump torques

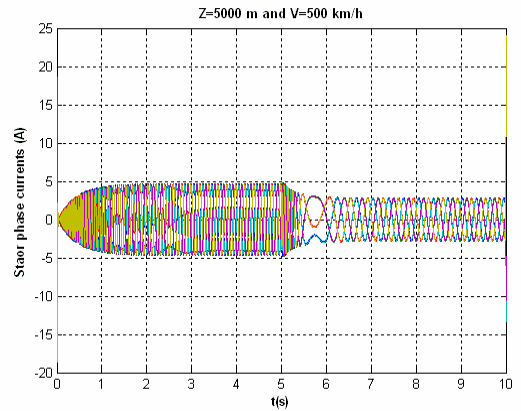


Figure 20: Evolution of the stator phase currents and set points

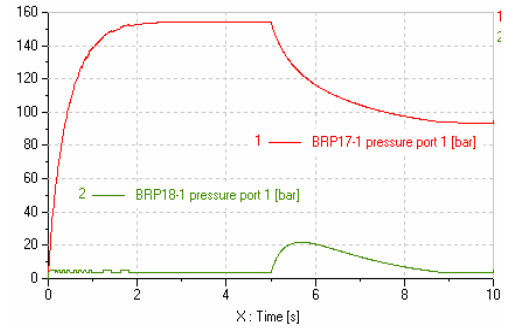


Figure 21: Evolution of the pressure in chambers 1 & 2

#### 4. EMULATION AND EXPERIMENTAL VALIDATION

The implemented and the validation of the EHA control laws and the aerodynamic load model requires the emulation of the EHA components. Two electric machines of an experimental platform are chosen. The permanent magnet synchronous machine emulates the permanent magnet synchronous machine of the EHA while the DC machine emulates the hydraulic pump, the jack, the control gear and the control surface submitted to the aerodynamic resistive torque (figure 22).

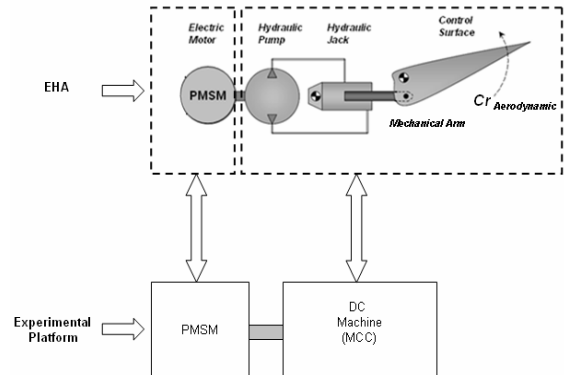


Figure 22: EHA emulation

The experimental platform used for the emulation is given by figure 23 and figure 24.

