Electro-hydrostatic Servo-actuators for Aircraft

LIVIU DINCA
Department of Avionics
University of Craiova
105, Decebal blvd.
ROMANIA

JENICA-ILEANA CORCAU
Department of Avionics
University of Craiova
105, Decebal blvd.
ROMANIA

MIHAI AURELIU LUNGU
Department of Avionics
University of Craiova
105, Decebal blvd.
ROMANIA

ALEXANDRU NICOLAE TUDOSIE
Department of Avionics
University of Craiova
105, Decebal blvd.
ROMANIA

Abstract: Some great aeronautic catastrophes were produced by the hydraulic liquid lost and from this by the impossibility of aerodynamic surfaces command. For this reason it appears necessary to replace the centralized hydraulic system with some small local hydraulic systems. This paper presents some problems concerning these actuators, a mathematical model for a such actuator and some numerical simulations.

Keywords: hydraulic actuators, aircraft command, mathematical models, hydrostatic actuators, hydraulic systems

1 Introduction

The hydraulic systems of big airliners reached some difficult problem along their exploitation period. Some of these problems produced great aeronautic catastrophes and for this reason the idea to replace the centralized hydraulic system with small local hydraulic systems appeared.

One of the most difficult problems was the lost of the hydraulic liquid. The hydraulic pipes sharing produce inevitably the lost of the hydraulic liquid and in consequence the impossibility to command the aircraft. Although the hydraulic system in double or even triple redundant, in some cases, structure damages produced the hydraulic pipes sharing for all the hydraulic system. Even the structure damage permitted to continue the flight, the airplane crushed because the impossibility of command.

Another problem of the centralized hydraulic system is the energetic efficiency of the actuation. The classical actuators use hydraulic servo-valves as command device. In these servo-valves at least 30% of the hydraulic power is lost. Considering although the power lost on hydraulic pipes and the other equipments, the maximum efficiency of the centralized hydraulic system is about 30 – 40 % . A small local hydraulic system reduce the lost power and so the efficiency is improved.

A third problem is an economical one. The classical hydraulic systems needs high maintenance costs and long time to replace one fault equipment. This leads to long time of out of service for the aircraft. One small local hydraulic system may be built as one compact servo-actuator, easy to replace in a fault case.

Using such actuators some problems concerning the hydraulic systems are transferred to the electrical systems. The local hydraulic circuit has a small pump acted by an electrical motor. The entire power needed for the aerodynamic surface actuation is now supplied by the electrical system instead the hydraulic system. But the electrical power distribution is more reliable as the hydraulic power distribution. For a big commercial airplane, the power supplied by the electrical system may reach 1MW if such servo-actuators are used.

2 Hydraulic schemes

Many hydraulic circuits were proposed to solve these problems. In figure 1 is presented a solution with a gear pump driven by an electrical motor. The gear pump has constant speed. The command device is a hydraulic servo-valve. But the hydraulic servo-valve is expansive and the problem of hydraulic power lost in this device remains.

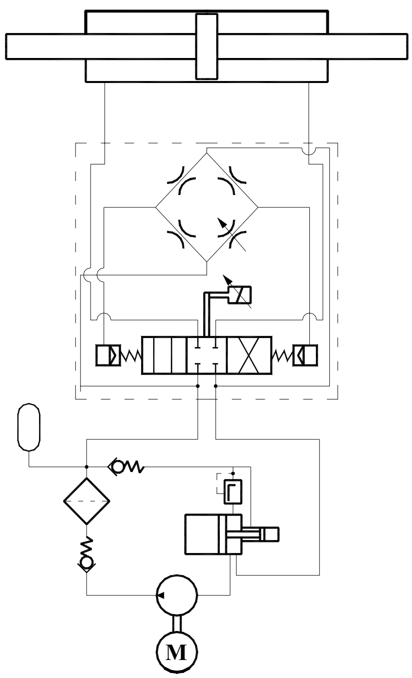


Fig. 1 Hydraulic local circuit with servo-valve

In figure 2 the hydraulic servo-valve is replaced by a proportional distributor. The cost is smaller, but remains the problem of power lost in this device. The problem of dynamical qualities of the actuator is more difficult to solve in this case. The proportional distributor is sluggish than the servo-valve and the response time of the actuator increase considerably.

The optimum solution, developed by some producers is presented in figure 3.

The pump supply direct the hydraulic cylinder, without another command device. Auxiliary elements such filters and valves are shown in figure 3. A check valve is used to fix the hydraulic cylinder in the neutral position when the pump or the motor fault.

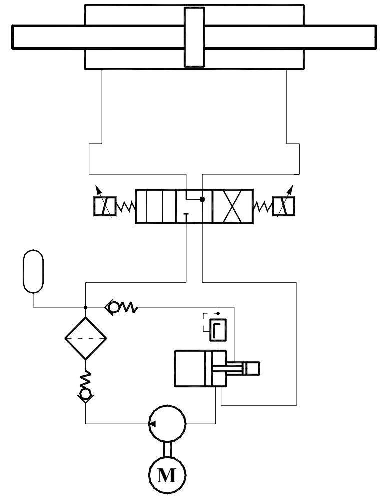


Fig. 2 Hydraulic local circuit with proportional distributor

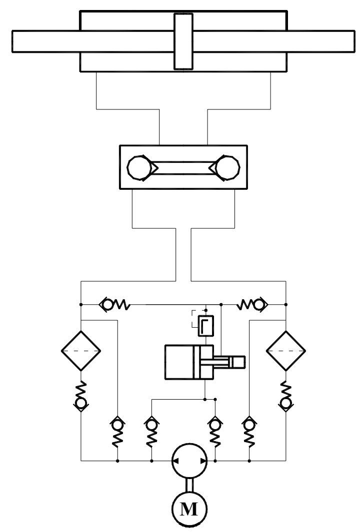


Fig. 3 Hydraulic local circuit driven by the motor speed

The hydraulic power lost only in short pipes, valves and filters is very small relative to the centralized hydraulic system provided with servo-valves. The efficiency of the hydraulic circuit in considerably improved.

The pump is a bidirectional gear pump and the command of the aerodynamic surface is obtained by the variation of the direction and the speed of the electric motor. The electric motor is a DC one and is provided with a controller which change the supply voltage accordingly the command received from the pilot.

One special problem is the hydraulic cylinder. Because the restrictive space on board it is not possible to use a bilateral rod cylinder. For this reason is used a special cylinder with one rod. This cylinder has the same effective area in the both movement directions [2].

In some variants the reservoir is replaced by a membrane hydro-accumulator which maintain the necessary pressure to the pump inlet. The hydro-accumulator is cheaper than the auto-pressurized reservoir and provide a sufficient quantity of hydraulic liquid.

3 The mathematical model

This study describe the behavior of a electro-hydrostatic servo-actuator shown in figure 3. A simplified scheme of the hydraulic circuit is presented in figure 4.

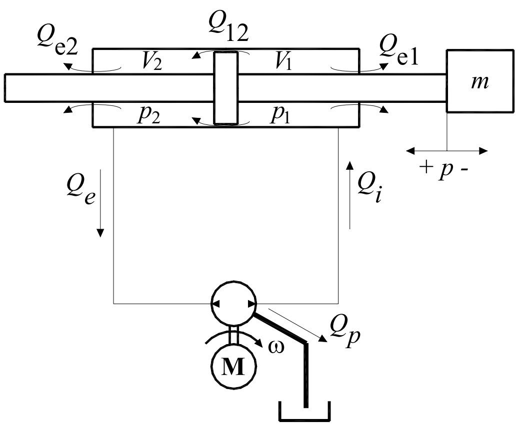


Fig. 4 Hydraulic circuit – simplified scheme

The flow rates through the pump and the leakage between the cylinder chambers, to the exterior and the pump lost flow rate are taken to account. So, the equations which describe the hydraulic cylinder functioning are the following:

$$(\beta V_{01} + Sz)\frac{\mathrm{d}p_1}{\mathrm{d}t} = Q_1 - Q_{e1} - Q_{12} - Q_{p1} - S\frac{\mathrm{d}z}{\mathrm{d}t} \quad (1)$$

$$(\beta V_{02} - Sz)\frac{\mathrm{d}p_2}{\mathrm{d}t} = -Q_2 - Q_{e1} + Q_{12} - Q_{p2} + S\frac{\mathrm{d}z}{\mathrm{d}t} \quad (2)$$

$$Q_{12} = c_{12}(p_1 - p_2) \quad (3)$$

$$Q_{e1} = c_1 p_1 \quad (4)$$

$$Q_{e2} = c_1 p_2 \quad (5)$$

$$Q_{p1} = c_2 p_1 \quad (6)$$

$$Q_{p2} = c_2 p_2 \quad (7)$$

$$Q_{pump} = D\omega \quad (8)$$

$$m\frac{\mathrm{d}^2 z}{\mathrm{d}t^2} = (p_2 - p_1)S - f\frac{\mathrm{d}z}{\mathrm{d}t} - kz - F_u \quad (9)$$

The linearization of these equations leads to

$$\frac{\mathrm{d}\Delta p_1}{\mathrm{d}t} = \left[-S\frac{\mathrm{d}z}{\mathrm{d}t} + D\omega - c_{12}(p_1 - p_2) - c_1 p_1 - c_2 p_1\right]\frac{1}{\beta V_1}, \quad (10)$$

$$\frac{\mathrm{d}\Delta p_2}{\mathrm{d}t} = \left[S\frac{\mathrm{d}z}{\mathrm{d}t} - D\omega + c_{12}(p_1 - p_2) - c_1 p_2 - c_2 p_2\right]\frac{1}{\beta V_2}. \quad (11)$$

If the movement is studied around the neutral point then $V_1 = V_2$ and from (10) and (11) ones obtain

$$\frac{\mathrm{d}(\Delta p_1 - \Delta p_2)}{\mathrm{d}t} = \left[-2S\frac{\mathrm{d}z}{\mathrm{d}t} + 2D\omega - c_{tp}(p_1 - p_2)\right]\frac{1}{\beta V} \quad (12)$$

For the DC motor we considered the model

$$L\frac{\mathrm{d}i}{\mathrm{d}t} = -Ri - k_e\omega + U, \quad (13)$$

$$J\frac{\mathrm{d}\omega}{\mathrm{d}t} = k_t i - B\omega - M. \quad (14)$$

Where

$$M = D\frac{1}{2\pi\eta_t}\Delta p. \quad (15)$$

Using these equation a simulation scheme in SIMULINK was obtained.

For the control loop two variants of controller were studied. One classical proportional controller and one fuzzy controller. The input of the system is one voltage and the output is the movement of the aerodynamic surface. The control loop is closed through the reaction voltage received from the position transducer of the aerodynamic surface.

The DC motor controller receive the error signal, amplify it and feed the motor. For the DC motor feeding, the saturation phenomenon was taken into account.

For the fuzzy controller was chosen a Mamdani controller.

We chose seven linguistically terms for the error (input of the controller) and for the output. The error domain was considered from -50 to 50 and the output from -1 to 1. The membership functions for the fuzification process were considered triangular type, uniform distributed from -1 to 1. The extremely functions were considered trapezoidal type with the maximum at -1 and 1 and extended to the error value of -50 and 50. A number of 49 fuzzy rules were obtained. These rules were constructed on the principle of correspondence between input and output. The bisector method was considered for defuzzification.

4 Numerical simulations

The simulation schemes obtained in SIMULINK were used to study the servo-actuator behaviour in different conditions. In the simulations presented in this paper the amplitude of the input signal was modified. The elastic constant k was kept, that means the aircraft speed was maintained constant.

The numerical values of the servo-actuator components parameters were obtained from technical specifications of the motor, pump and cylinder.

Parameters of actuated element:

- mass m	20 kg
- viscous friction coefficient f	10000 Ns/m
-spring constant k	108979,9 N/m

Hydraulic cylinder:

-piston section S	7,5 cm^2
-stroke l	13,7 cm
-pipes volume V_0	0,39 cm^3
-leakage constant between chambers c_{12}	$2 \cdot 10^{-13} m^3 / Pa \cdot s$
- leakage constant to exterior	$1{,}68 \cdot 10^{-13} m^3 / Pa \cdot s$

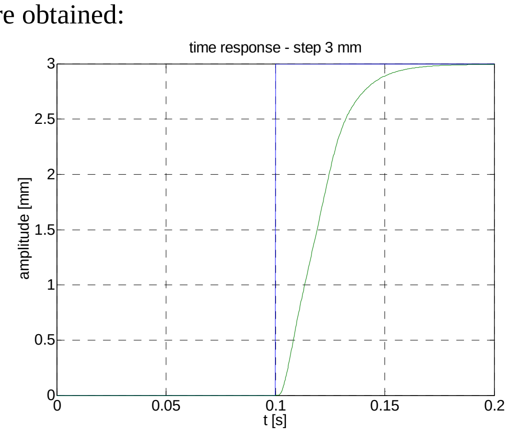
Pump parameters:

- displacement D:	0,169 cm^3/rad
- pump leakage constant	$2 \cdot 10^{-13}\ \mathrm{m}^3 / \mathrm{Pa} \cdot \mathrm{s}$

Electric motor parameters

-coil inductance L:	1 mH
-coil resistance R:	0,35 Ω
-back-EMF constant k_e:	0,063 V/rad/s
-torque constant k_t:	0,0663 Nm/A
-momentum J:	$2{,}40 \cdot 10^{-5}$ kgm^2
-friction coefficient B:	0,004 kgms

After the numerical simulations the following results were obtained:



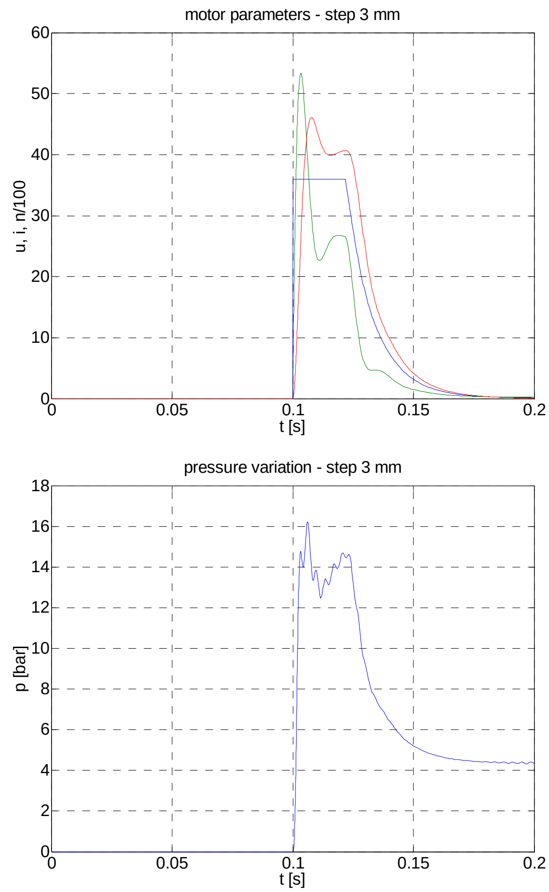
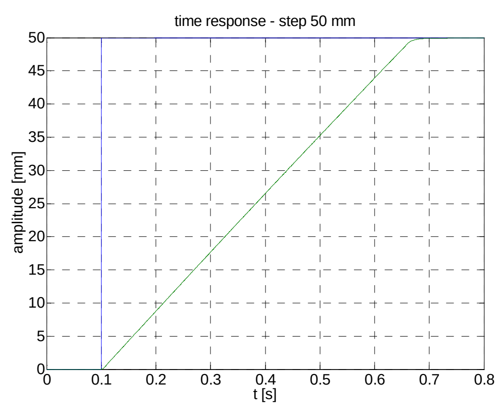
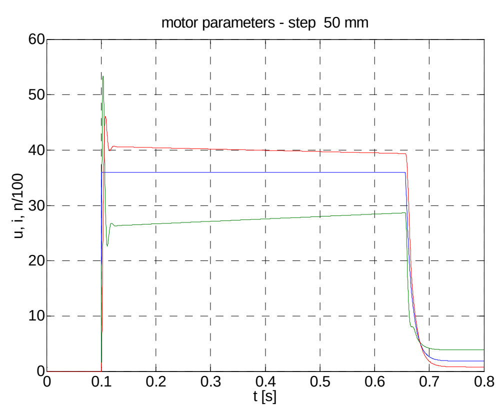


Fig. 5 System behaviour P controller, step 3 mm





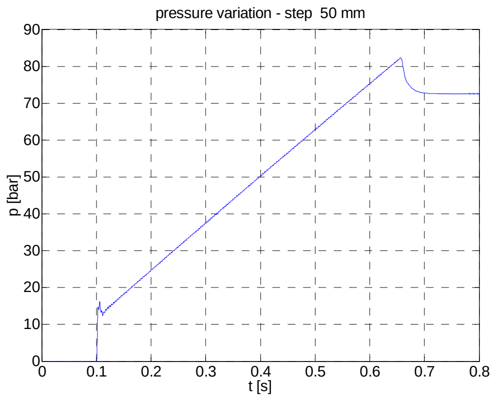
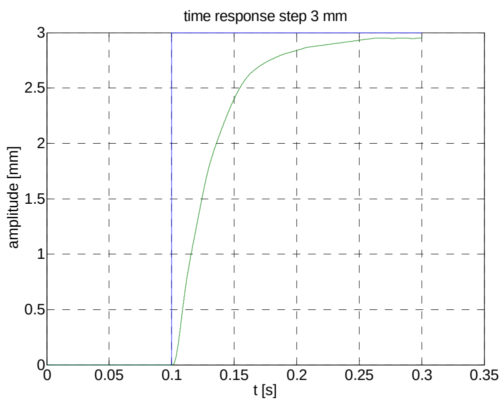
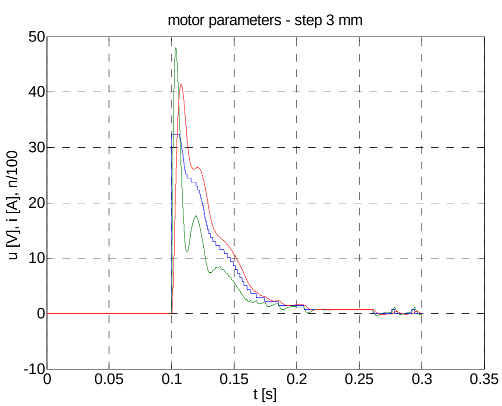


Fig. 6 System behaviour P controller, step 50 mm





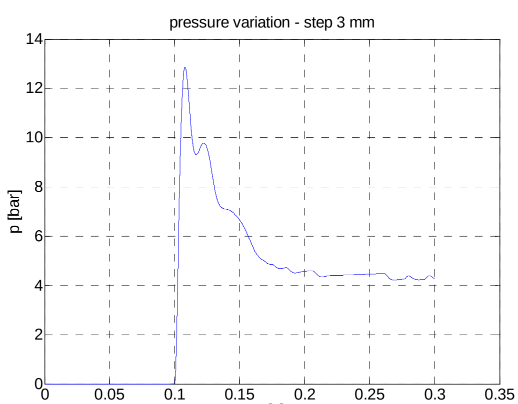
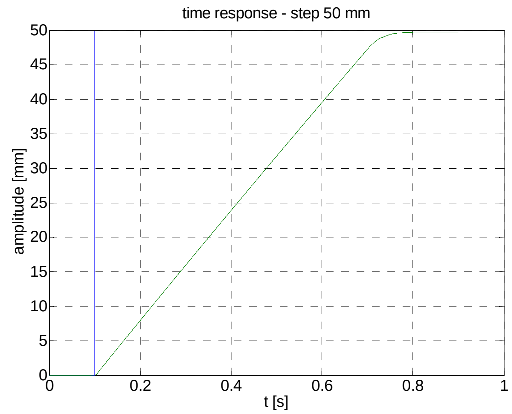
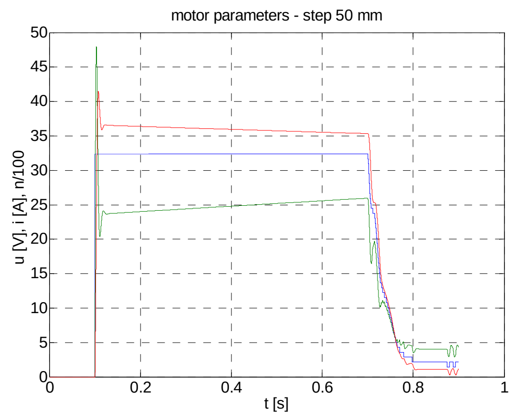


Fig. 7 System behaviour fuzy controller, step 3 mm





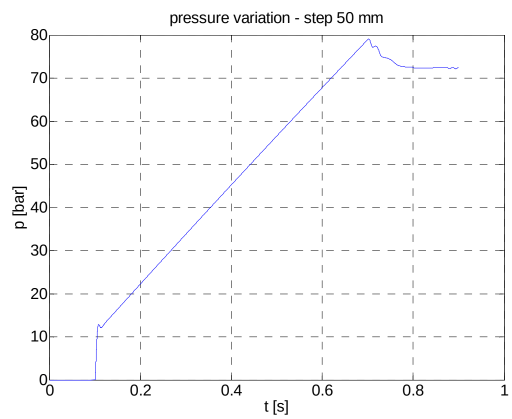
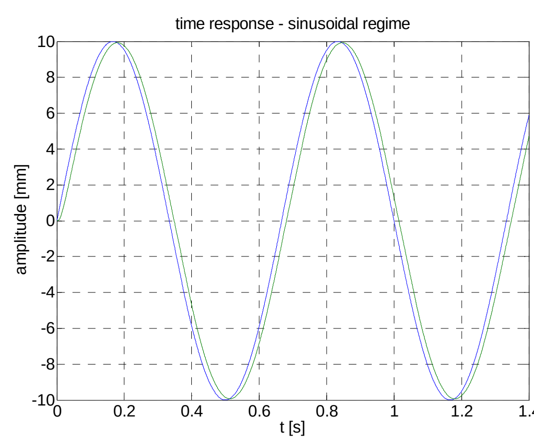


Fig. 8 System behaviour,fuzy controller, step 50 mm



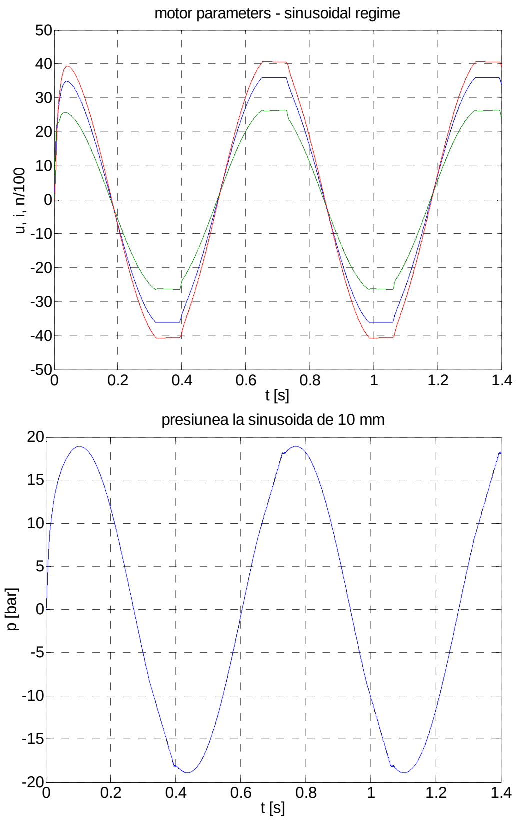


Fig. 9 System behaviour – sinusoidal regime

5 Conclusions

The results obtained from the numerical simulations reflect a good behaviour of the servo-actuator regarding the time response at step signal when a classical P controller is used. The time response parameters are in the limits imposed for the aircraft command surfaces actuators.

The electric motor reach the saturation regime even at 3 mm step signal input, but this is not an impediment in the servo-actuator functioning.

When a fuzzy controller is used, the servo-actuator is sluggish so it can be improved to obtain better results. One way to improve the fuzzy controller is to modify the membership functions in order to accelerate the servo-actuator movement.

Difficult problems in this actuator implementation will appear in the electric power distribution. This actuator needs high power invertors when it is used on big aircraft. Despite this, this type of servo-actuator it is expected to be the future in the aerodynamic surfaces actuation.

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