Principal servocontroller failure modes and effects on active flutter suppression

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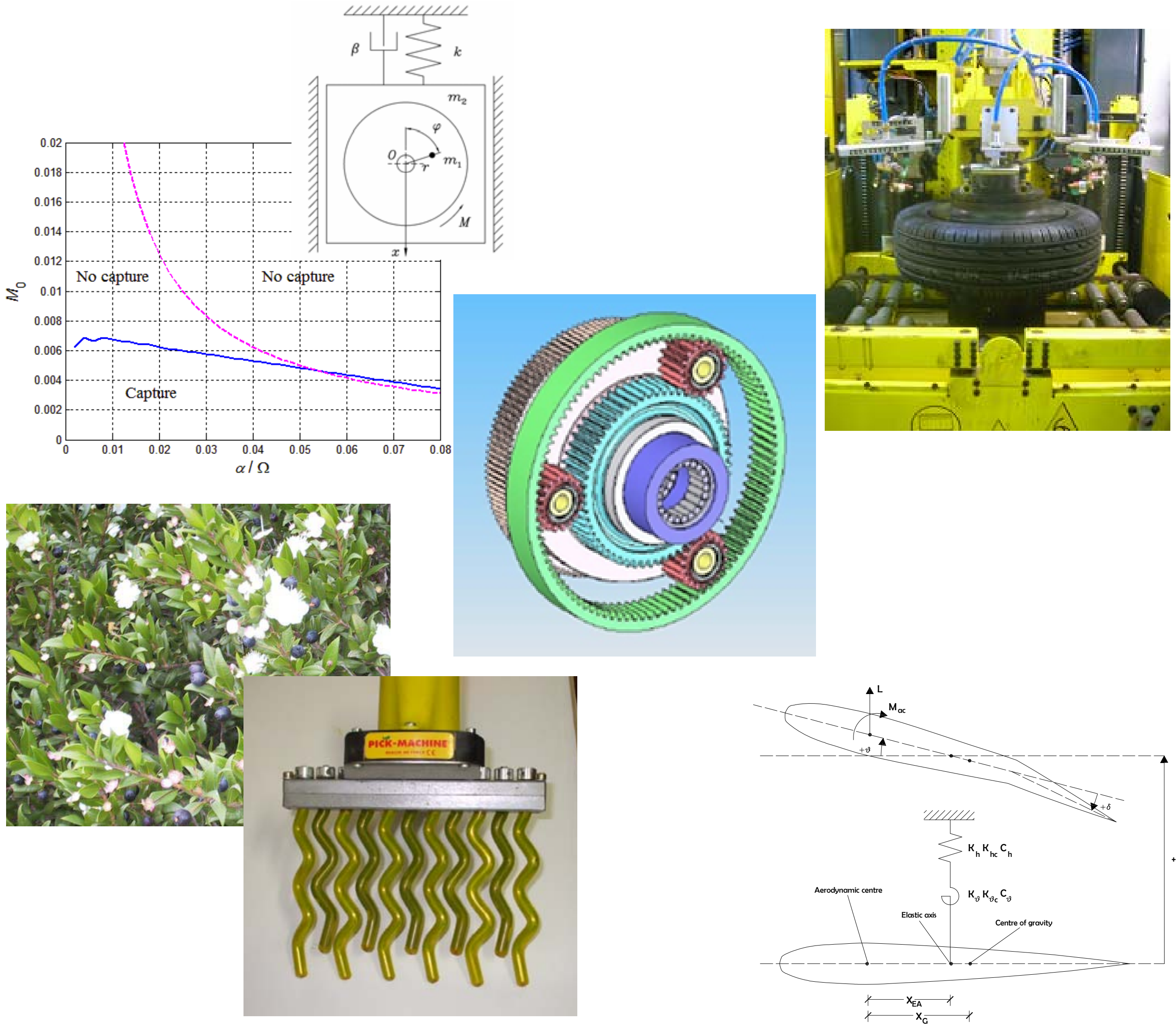

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PRINCIPAL SERVOCONTROLLER FAILURE MODES AND EFFECTS ON ACTIVE FLUTTER SUPPRESSION

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ABSTRACT

Conventional active flutter and vibration control technology relies on the use of aerodynamic control surfaces operated by servo-hydraulic actuators, which can be affected by some specific types of failure. In order to assure a sufficiently high safety degree, it is necessary to verify the dynamic behaviour of the whole system when a defined failure occurs. The purpose of this paper is to analyze the aeroservoelastic behaviour of a typical wing with active flutter suppression performed by a hydraulic servomechanism equipped with a defined proper control law (relating the required surface deflection angle to speeds and acceleration of the main aerofoil surface) and affected by the principal modes of servocontroller failures. Active control and its failure modes have been implemented within the model of a representative actuation system acting on a wing structure embedded in a defined aerodynamic field.

Keywords: Failure, flutter, flight controls, active suppression.

1 INTRODUCTION

Aeroelasticity is the mutual interaction between deformations of the elastic structure and aerodynamic forces induced by the structure deformations. Combined, these effects may cause an aircraft structure to become unstable above a defined value of flight speed. If the interaction between deformations and aerodynamic forces involves also the inertia, the phenomenon, called flutter, is an oscillatory instability that occurs when the structural damping transitions from positive to negative due to the presence of aerodynamic forces. During this transition, two modes of vibration coalesce to the same frequency and achieve an aeroelastic resonance. Bending and torsion are the two most common vibration modes of a wing which coalesce to flutter. In modern aircrafts the use of automatic flight control systems with powered control surfaces has further complicated the problem.

This interaction between structural dynamics, unsteady aerodynamics and the flight control system of the aircraft, known as aeroservoelasticity, has been and continues to be an extremely important consideration in many aircraft designs. To prevent undesirable aeroelastic effects, the stiffness of the wing must be increased, adding weight to the aircraft and decreasing the overall performance: this approach is known as "passive control". A recent alternative to passive control is the so called "active control" through feedback to control surfaces (conventional technique), or, more recently, through feedback to active materials. These vibration control technologies allow flight vehicles to operate beyond the traditional flutter boundaries, improve ride qualities, and minimize vibration fatigue damage. Many control strategies have been applied to suppress flutter or to control unacceptable wing motion. Conventional active flutter and vibration control technology relies on the use of aerodynamic control surfaces operated by servo-hydraulic actuators. In this conventional configuration the flutter and vibration suppression algorithms are implemented through the servovalve/hydraulic actuator, capable of producing (if necessary in presence of large oscillation amplitude) large forces and large surface displacement, but having some limitations, such as limited actuation speed in saturation conditions and limited frequency range. In contrast, active materials technologies offer high-frequency responses but

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their typical shortcomings are limited forces and displacements performed.

Generally, these problems have been already studied by several authors, but no work specifically concerns the effects on the aeroelastic system of the most important failure modes affecting the flutter servocontroller, as:

- servovalve feedback spring failure
- hydraulic system pressure drop
- whole active flutter control failure
- piston seizure
- piston internal sealing failure.

The aim of this paper is the analysis of the aeroservoelastic behaviour of a typical wing with active flutter suppression performed, through a defined control law, by a fly-by-wire hydraulic servomechanism affected by the aforesaid modes of servocontroller failures.

2 DESCRIPTION OF AEROSERVOELASTIC MODEL

Figure 1 shows the typical wing section that is used to derive the structural equations of motion. The two degrees of freedom associated with the aerofoil motions are the vertical displacement *h* and the pitching displacement *θ*.

The displacements are restrained by a pair of springs attached to the elastic axis with linear spring constants K_θ and K_h and cubic one $K_{\theta c}$ and K_{hc} respectively. The airfoil is equipped with a trailing edge moving surface, whose position *δ* depends exclusively on the servomechanism position and is not affected by the aerodynamic and inertial loads. The servomechanism position depends, through its dynamic model, on the output of an adequate flutter suppression control law. The aerodynamic model computes lift and pitch moment related to the aerodynamic centre as a function of the dynamic pressure, the initial value of the angle of attack *α*, the pitching displacement *θ*, the vertical and pitching rates and the surface deflection angle *δ*.

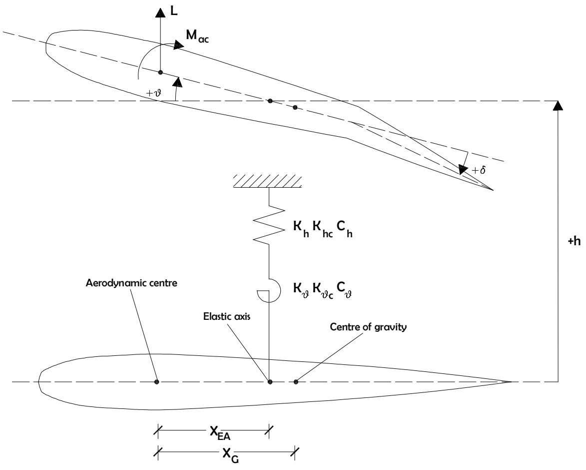

Figure 1 Aeroelastic parameter definition.

The structural dynamic model computes vertical and pitching accelerations related to the elastic axis as a function of aerodynamic loads L and M_{ac}, inertial loads, weight, structural damping and stiffness. The structural damping is considered as a linear function of the speed, while the structural stiffness is modelled as a linear and cubic function of the displacement. The sign of the cubic coefficient takes into account the softening or hardening effects. The actuation system of the aerodynamic surfaces consists of a Power Control and Drive Unit (PDU, equipped with position transducers and tachometers), directly connected to the lever arm of the surfaces. The system control is performed by an Electronic Control Unit (ECU), which closes the position control loop. The PDU contains the hydraulic jack and the control valve.

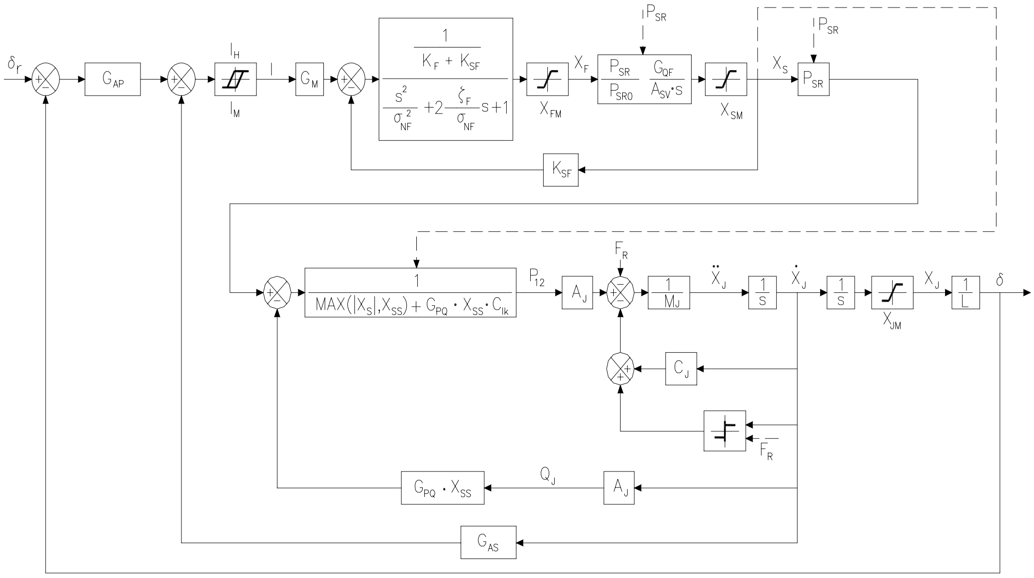

Figure 2 Block diagram of the model of the actuation system.

The model of the actuation system, as reported in figure 2, takes into account the hydraulic and mechanical characteristics of all system components as follows:

- Coulomb friction in the PDU-surface assembly;
- third order electromechanical dynamic model of the servovalve with first and second stage ends of travel;
- fluid-dynamic model of the servovalve taking into account the maximum differential pressure, eventually time varying, performed by the hydraulic system1;
- dynamic and fluid-dynamic of hydraulic jack taking into account, beside the above mentioned Coulomb friction, viscous friction and internal leakage.

The high complexity of the actuation system servomechanism model is requested by the necessity of taking into account the effects of the above mentioned several nonlinearities on the effectiveness of the flutter suppression active control.

Active control has been implemented within the proposed model, in order to investigate active means of flutter suppression via control surface motion. A simple control law is used which relates the required surface deflection angle δ_r to the speed and the acceleration of the main aerofoil surface (heave and pitch degrees of freedom). Hence, δ_r is evaluated according to the following equation:

$$\delta_r = G_{h2}\,\ddot{h} + G_{h1}\,\dot{h} + G_{\vartheta 2}\,\ddot{\vartheta} + G_{\vartheta 1}\,\dot{\vartheta} \qquad (1)$$

where the G's are the gains of the system.

3 SYSTEM COMPUTATIONAL MODELLING AND RESULTS

The above described models have been used to build a mathematical model of the whole system and a dedicated computer code has been prepared. A structural model having linear and cubic softening spring characteristics around the pitch axis and linear along the vertical displacement is considered. The aerodynamic model is described as linear and the considered flight speed is slightly greater than the critical flutter speed.

Some simulations have been run in different failure conditions, in order to verify the criticality of the actuation system failures on the flutter suppression active control. All the following figures show the behavior of the system in terms of vertical displacement h and pitching angular displacement θ: their trend is typically oscillatory, characterized by a frequency slightly depending on the corresponding amplitude, having an average value of approximately 14,5 Hz. The curves reported in the figures represent the envelopes of the eventually damped oscillations.

Figure 3 shows the behaviour of the system characterized by a fully operational (no failures) active flutter control, in terms of vertical displacement h and pitching angular displacement θ, employing the control law (1) applying a not null value only to the gain $G_{\theta 2}$, because this is a satisfying solution as discussed in [1].

In this case the slow growth of the oscillations amplitude, following the application of a large step perturbation concerning the pitching displacement at time t = 1 s, is suppressed by the active flutter control.

This case must be considered as reference condition for the following simulations.

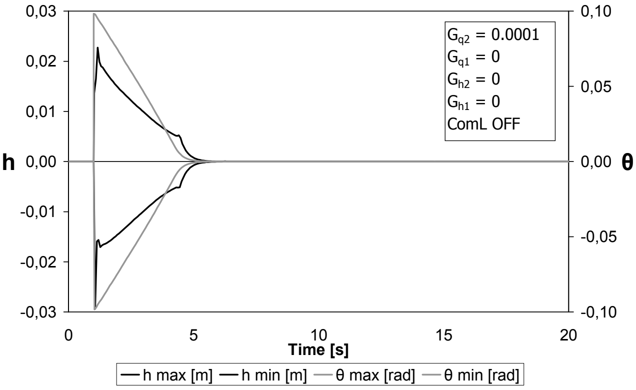

Figure 3 Fully operational system.

Figure 4 shows the dynamic behaviour of the system in the servovalve feedback spring failure condition. The failure occurs at time t = 2 s. With respect to Figure 3, the behaviour is substantially identical as long as the amplitude of the servomechanism input command is so large to produce end of travel displacements of the servovalve spool, because in this condition the feedback spring is practically ineffective. Some small differences are detectable when the amplitude of the input command is substantially reduced and the ends of travel are no longer important in the displacement of the servovalve mechanical elements. However the servomechanism, though affected by a limit cycle giving rise to fatigue damage, is able to perform a response on average close to the commanded position. In fact the limit cycle frequency is higher than any structural frequency, so its effect is marginal for the aeroelastic phenomenon.

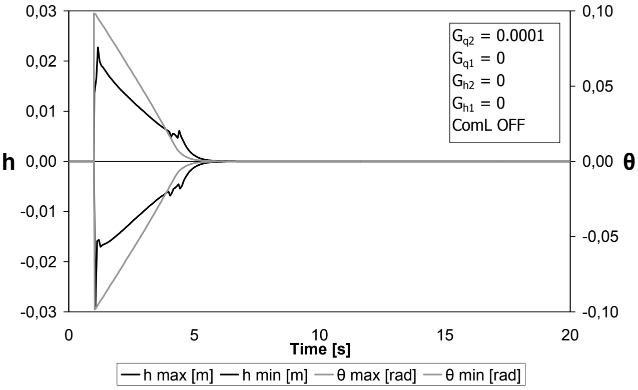

Figure 4 Feedback spring failure.

Figure 5 shows the dynamic behaviour of the system in case of hydraulic system pressure drop to a very low value (1 MPa) occurred at time t = 2 s, when both the servovalve spool and the moving surface are far from the centered position. The available actuation speed at a very low pressure value is very small, so the moving surface should no longer be able to retract to the null position. In this case the surface is progressively driven, through a series of oscillations, to the null position mainly by the aerodynamic load, overcoming the supply pressure effect. However the reduced available actuation rate prevents an effective flutter corrective action.

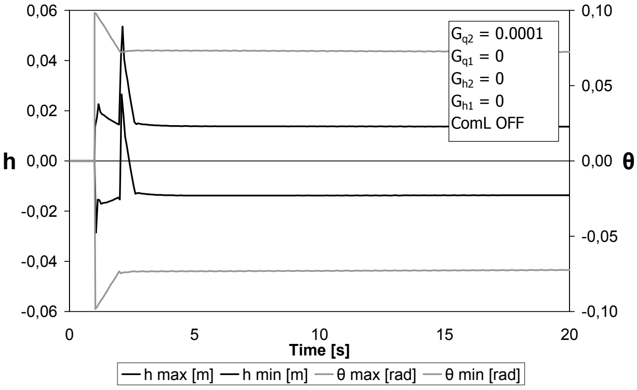

Figure 5 Hydraulic pressure drop to a very low value.

Figure 6 shows the dynamic behaviour of the system in case of hydraulic system pressure drop to a higher value than the previous case (5 MPa) occurred at time t = 2 s. The available actuation rate is higher than in Figure 5, so the flutter corrective action is slightly more effective.

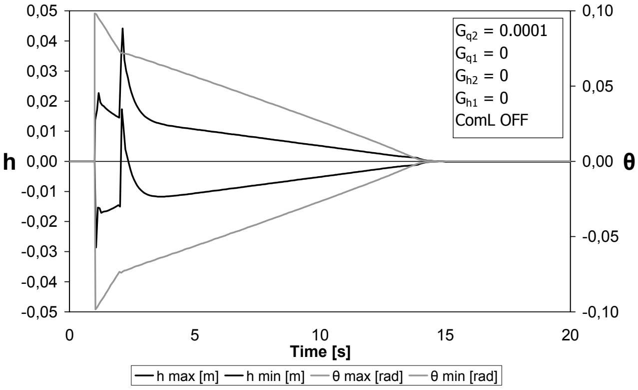

Figure 6 Hydraulic pressure drop to a higher value than the previous case.

Figure 7 shows the same pressure drop of Figure 5 at time t = 2 s, then followed by a pressure restore to the normal value (20 MPa) at time t = 5 s. As expected, it can be noted, till to 5 s, the same behaviour reported in Figure 5. At the pressure restore the corrective ability of the servomechanism is now fully available, and the behaviour of the system is similar to Figure 3.

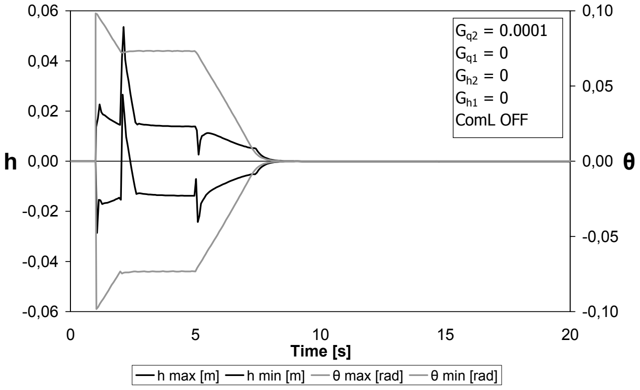

Figure 7 Hydraulic pressure drop and subsequent restore.

Figure 8 shows the dynamic behaviour of the system in case of whole active flutter control failure, intended as the loss of the servomechanism input command (constantly null), without any failure strictly regarding the servomechanism integrity. When the failure occurs, the surface is quickly retracted to the null position, remaining ineffective through the following part of the simulation. As expected, the flutter phenomenon is slightly divergent, as in case of absence of active flutter control.

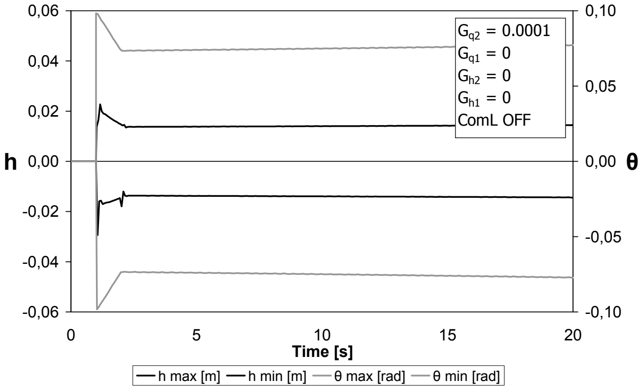

Figure 8 Whole active flutter control failure.

Figure 9 shows the dynamic behaviour of the system in case of incipient piston seizure, modelled as a marked rise of the friction force to a value slightly lower then the stall piston one. As a consequence, the servocontrol actuation rate, still possible, is however lower than usual, so the corrective capability is reduced.

Figure 10 shows the dynamic behaviour of the system in case of piston seizure, modelled as a more marked rise of the friction force to a value higher then the stall piston one. When the failure occurs, the surface is stopped in a position far from the centered one, and its flutter corrective action is lost. More, the not null surface position is able to keep the wing structure in a deformed position, as it is evident mainly in terms of vertical displacement.

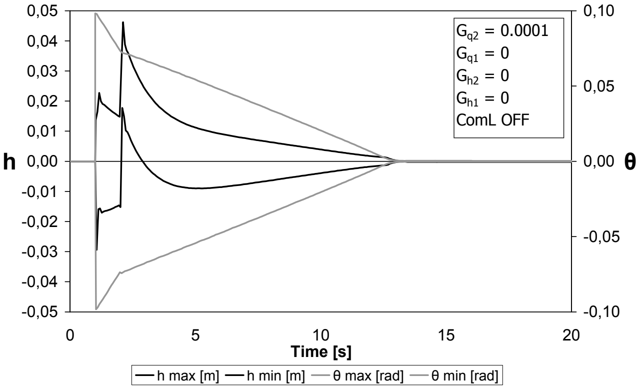

Figure 9 Incipient piston seizure.

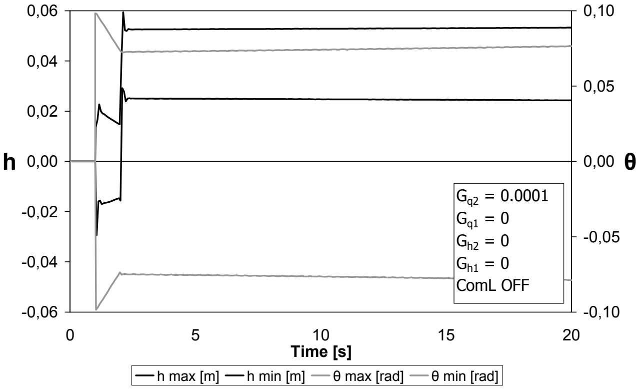

Figure 10 Piston seizure.

Figure 11 shows the dynamic behaviour of the system in case of marginal piston internal sealing failure, modelled as a medium growth of its leakage coefficient. Under low to medium aerodynamic loads, the actuation capability is slightly reduced (lower rate) but substantially preserved. As a consequence the flutter corrective action is slightly lower than the case shown in Fig. 3.

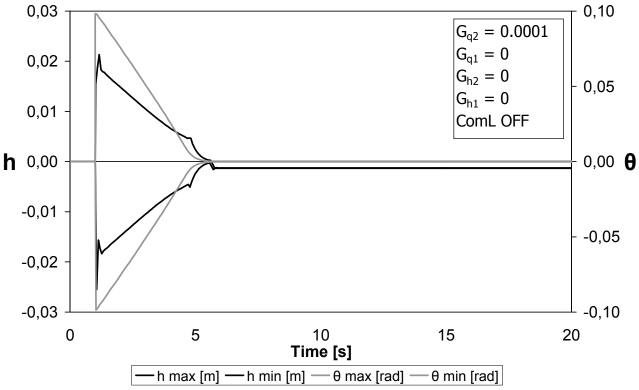

Figure 11 Marginal piston internal sealing failure.

Figure 12 shows the dynamic behaviour of the system in case of piston internal sealing failure, modelled as a large increase of its leakage coefficient. In this case the actuation capability is markedly reduced even under low aerodynamic loads. On the contrary the aerodynamic load is often able to overcome the input command and the surface deployment is mainly the consequence of the load itself. This effect produces a negative corrective action, so developing higher divergence rate.

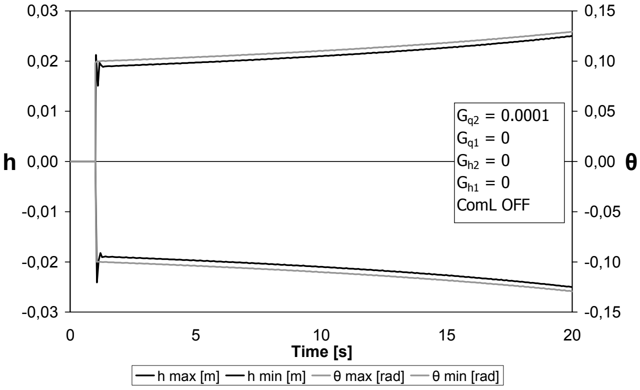

Figure 12 Piston internal sealing failure.

4 CONCLUSIONS

The results presented in this work are obtained in case of not redundant servosystem; so the failure effects are not limited by the action of the operative portion of an eventually redundant device. However the results are significant mainly for their conceptual aspects and show the possible criticality of a singular failure in a not redundant device. It can be noted that the more critical failures are those concerning the loss of the piston internal sealing, the total supply pressure drop or the total piston seizure. Sealing damage and pressure drop can be efficiently overcome by a proper redundancy; on the contrary, the piston seizure, particularly in case of force summed redundancies, must be considered seriously critical because the operative portion of the system may be incapable of overcoming the failure effects.

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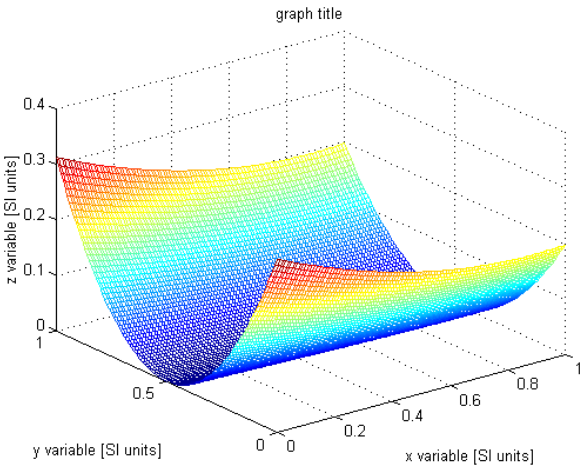

Figure 1 Simple chart.

Table VII - Experimental values

Robot Arm Velocity (rad/s)	Motor Torque (Nm)
0.123	10.123
1.456	20.234
2.789	30.345
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