# AERONAUTICAL STEERING SYSTEM DYNAMIC MODELING

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***Abstract.*** *Electro-hydraulic systems are commonly used to control heavy vehicles steering. Aircraft steering have developed into high performance and high reliability systems. Thanks to fairly recent technological growth, these systems are becoming optimized to comply with most variable requirements, especially in terms of performance under extreme conditions. Due to the operational envelope of an aircraft, extremes conditions are a constant in aeronautical systems. The steering system is regularly exposed to temperatures of -54 $^oC$ for hours and then suddenly brought to 50 $^oC$. Such points have to be analyzed in order to fully complywith its function. Using bond-graph methodology a complete steering system is modeled, integrating mechanical, hydraulic and control domains into a one-dimensional dynamic model. The mentioned method is supporting an increase in acknowledgement of complexes systems. Different from traditional signal flow modeling method, the bond-graph with a correct tool enables systems engineers to focus on physical phenomena with very little or none complex mathematical treatment. In the proposed model several physical aspects of the system are exposed. A brief introduction to bond-graph methodology is presented, as well as its comparison to the most commonly accepted signal flow substitutes. In this study case a regional aircraft steering system architecture is computationally reproduced and validated. The effect of external variables is experienced and analyzed. Temperature affects directly the hydraulic fluid`s characteristics which have an effect on the hydraulic manifold control dynamics and on the system response itself. This is done by a sensitivity analysis. A method to identify most significant variables into certain system response parameters is presented. Once the variables of interest are recognized, an optimization process is performed relating them to performance criteria.*

***Keywords***: *steering, dynamic, modeling, simulation*

## 1. INTRODUCTION

Aeronautical steering system can be of various types. Small aircraft often use purely mechanical systems, directly connecting the pilot's foot commands to the nose landing gear wheel – this is valid for regular tricycle landing gear configuration, which is the absolute majority of the cases of the industry. As the aircraft gets larger and heavier, the pilot is no longer able to provide enough power to keep the system under safe operation.

Powered systems are the solution to provide adequate control for larger aircraft. This category of steering systems also has variations: electrical or hydraulic powered, being the last one most found at present time. The simplest system architecture with a control loop is shown at

Figure **1**.

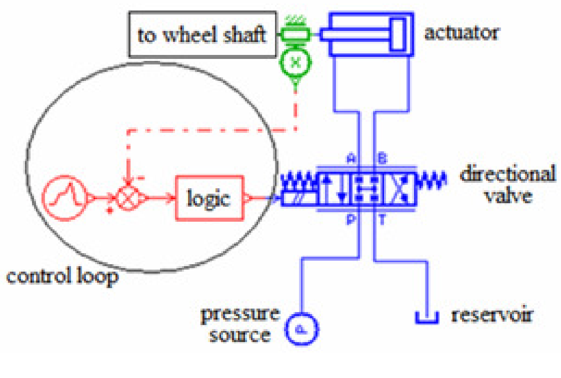


Figure 1 – Hydraulic powered position control system

All hydraulic powered systems must have a pressure supply, a directional valve and hydraulic actuators. The directional valve is often combined with other components on a single manifold to comply with the system`s complementary yet of most importance functions: to provide shimmy damping on operation and automatic free castor engagement in failure mode.

The hydraulic actuator configuration can be of the rotational type, directly connected to the steering shaft or of the linear type, mechanically linked to the shaft on a push – pull configuration or with the use of a rack and pinion, which is the case of the focus of this study.

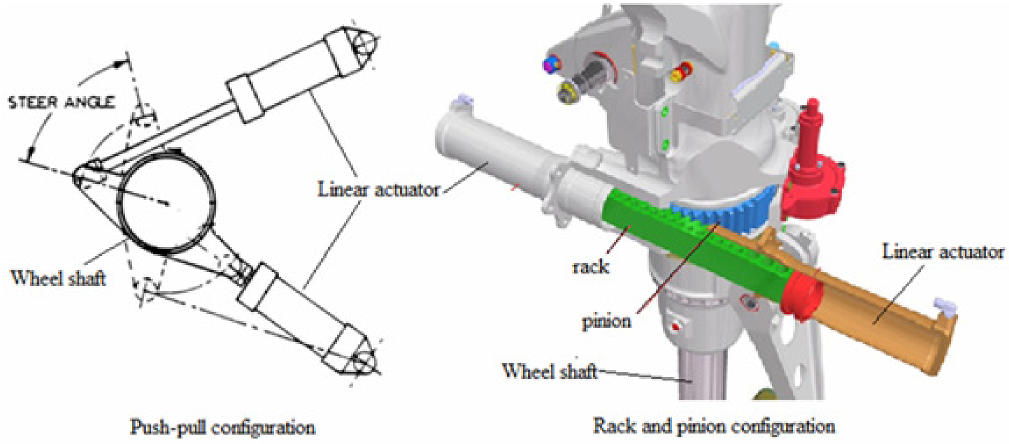


Figure 2 – Link configuration

All the above mentioned characteristics must be analyzed and carefully chosen to reach best solution for each given application. The problem investigated here is classified as a design review, when there`s an already functional design, first by modeling it and validating its behavior and afterwards proposing the most effective design change to improve the system performance under extreme temperature condition.

It`s important to point that the parameters shown on the graphs are de-characterized by non-identified units to protect sensitive information and should not be used as reference to any other study or work.

## 2. DEVELOPMENT

Two known modeling methodologies were assessed to construct the steering system dynamic modeling: signal and power flow. The first one can be implemented by the Mathworks Simulink, and the second can be represented by bond-graph methodology. Upon the available dynamic modeling techniques, the bond-graph method was the chosen one. The software platform LMS AMESim is well known as a good tool to model multi-domain complex models using on its base the bond-graph methodology.

Figure 3 shows the complexity differences of both approaches for a simple hydraulic actuated control system.

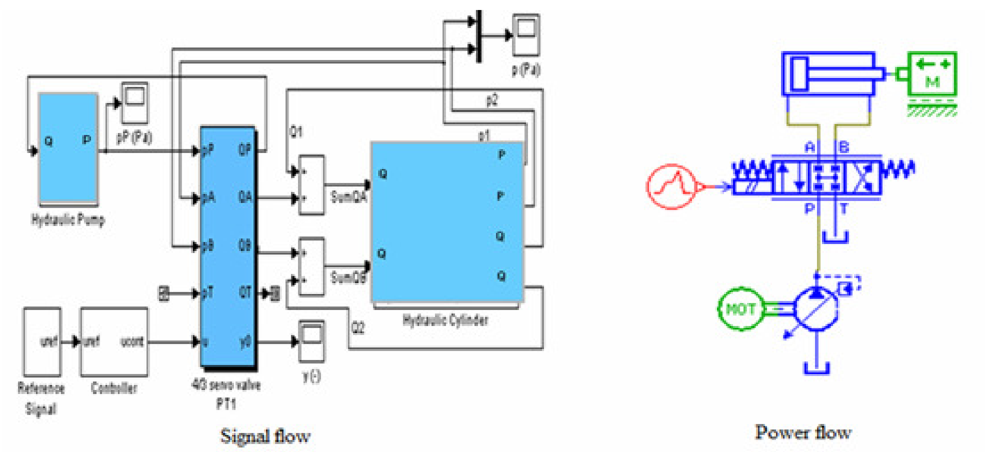


Figure 3 – Representation comparison

Even though both techniques use the “black-box” concept, the power flow is much more pictorial and the energy relationship between these boxes most of the cases reflects exactly the physical bond existing in the real system.

### 2.1. System detailed description

In order to fulfill all operational requirements of an aeronautical steering system, besides the aforementioned components, several others have to be included on the hydraulic architecture. An explanation on all of the chosen system components is followed.

Figure 4 is the complete scope of the mechanical and hydraulic parts of the system. Apart from the components on the figure, only the input signal and control logic is excluded from the diagram. They will be shown later.

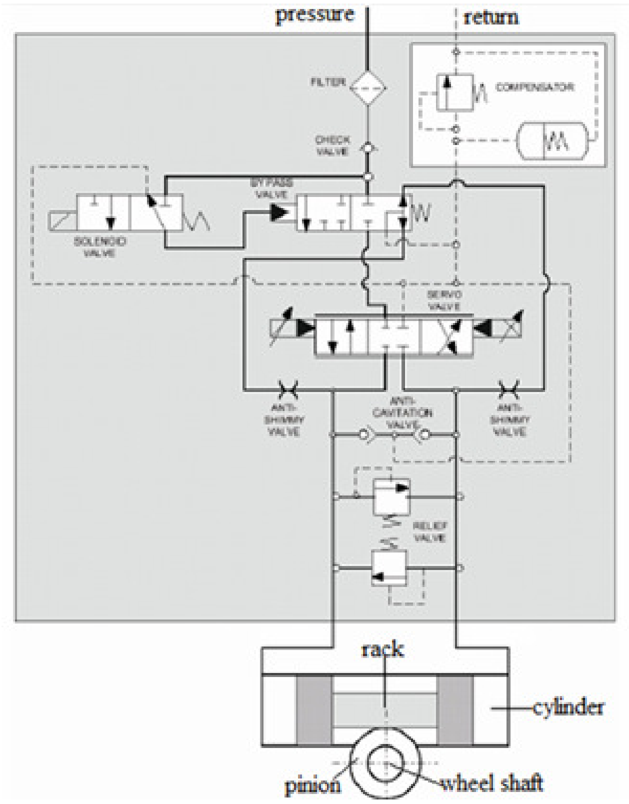


Figure 4 - hydraulic and mechanical architecture

The inlet filter protects the system from external contamination that may be contained on the pressure supply hydraulic system. Downstream from in, the check valve guarantees that the hydraulic manifold and associated components are always filled with fluid, even on the case of hydraulic supply failure.

The solenoid valve opens when energized. It connects the pressure input to the pilot of the bypass valve which opens and connects the pressure directly with the directional valve. When the solenoid acts, the steering system is engaged; otherwise it is on free castor mode.

The directional valve is commanded electrically and is responsible to control the pressure to each of the cylinder chambers, acting on the wheel shaft as needed.

On free castor mode, the bypass valve connects both cylinders chambers, what allows fluid to be transferred from one chamber to the other and wheel position free movement. In this situation the anti-shimmy restrictor valves damp undesired position variations, keeping the system under control.

Anti cavitation-valves are placed on the cylinders input/output lines to maintain their chambers always with hydraulic fluid on the event of rapid wheel position variation due to external forces, what otherwise would create very low pressure points resulting in gas bubbles and consequently cavitation damages.

The compensator provides the minimum level of hydraulic pressure and volume dedicated to the steering system. This is of extreme importance to the correct operation of the shimmy restrictor valves and also to compensate the thermal volume expansion. The inbuilt relief valve protects the system from overpressure and overload situations possibly created by operation faults on aircraft towing procedures. The rack and pinion assembly transmits the hydraulic power to the wheel steering shaft of the nose landing gear.

Additionally to all the above components, the hydraulic power supply behavior and capabilities have great impact on the overall steering system performance. A description of the main characteristics of the hydraulic power generation system, which affects the steering, is given next.

The hydraulic system has two variable displacement pressure compensated pumps; the primary connected to the engine's gear box and the secondary, with lower flow capability, connected to an electric motor, which is used under specific flight phases or failure situations.

Other functions that improve the system performance and ease the operation are related to the closed loop control of the wheel position. Two important features that are included are a non-linearity of the pilot input signal and a maximum possible steer range dependent on the aircraft ground speed. The first aims to achieve greater sensitivity of the control when the deflections are small, while the second imposes a safety protection to harmful commands of the steering at high speeds. As an example, Figure 5 shows a typical behavior of the described features.

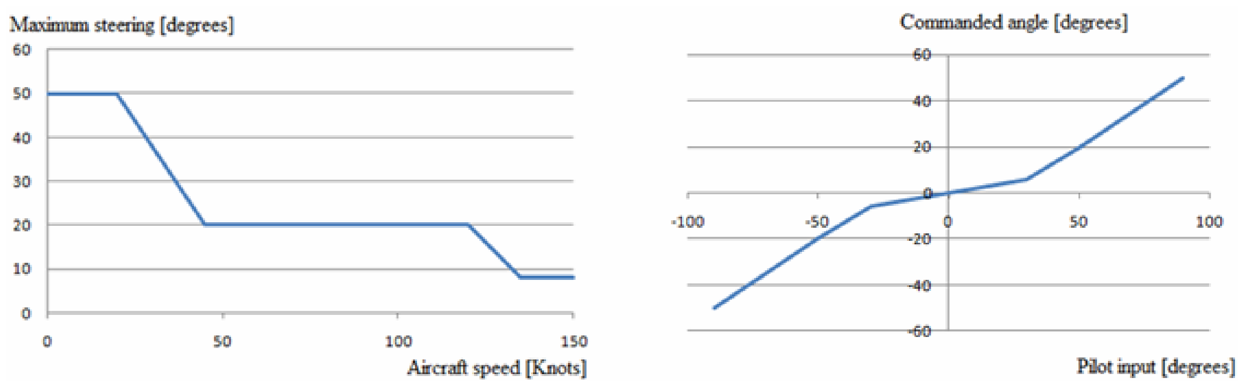


Figure 5 – Control implemented features

## 2.2. System modeling

Each component has received specific dynamic models thru basic equations of the physical phenomena that they were intended to represent. Some of the main models will be described in this section, but firstly Figure 6 reveals the complete system dynamic model conception.

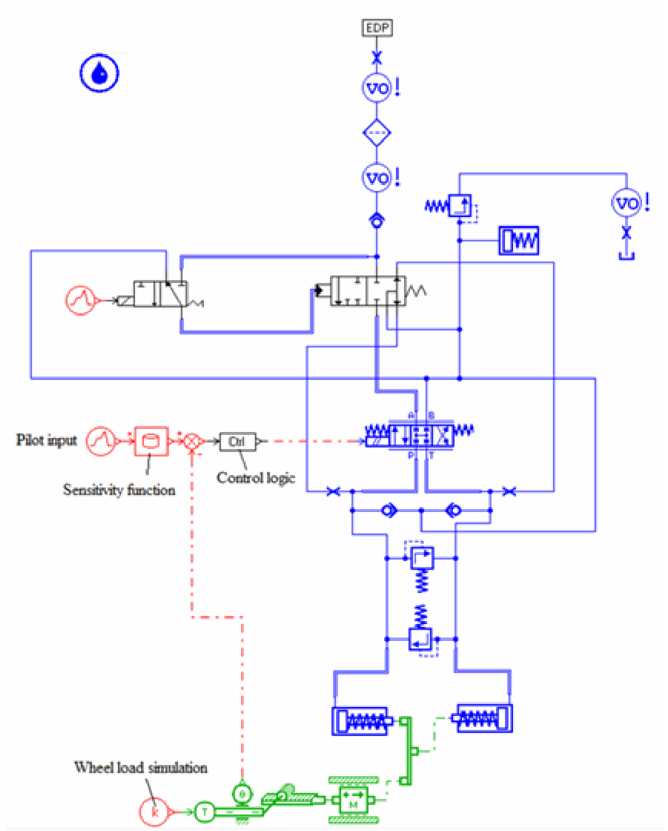


Figure 6 - Complete model

### 2.2.1 . Considerations

A simple restriction can be mathematically modeled starting with Bernoulli equation and developing it to adapt to a given scenario. As a result, one will find a pressure drop as an effect of the flow thru the restriction. As all off the shelf components provided by AMESim, further in deep documentation, including formulae development is available on the software handbook (LMS Imagine, 2006). Figure 7 represents the behavior of one of the restrictions parameterized to be used on the system under a hypothetical input pressure profile. Note that the same base equation may be used whenever a component requires representing the physical phenomena of hydraulic resistance, which is the case of all the hydraulic components of the scheme.

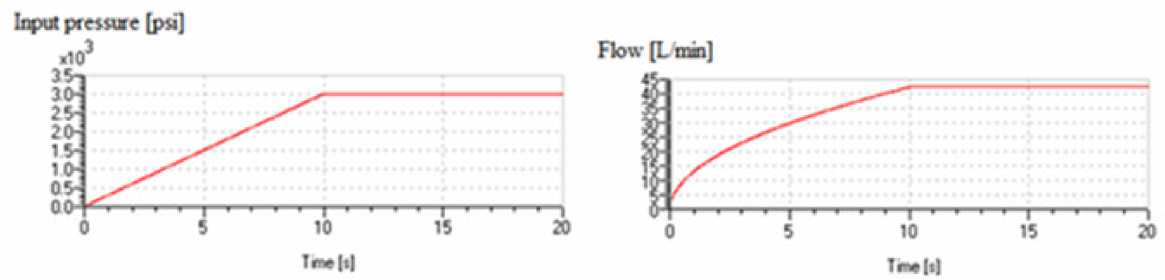


Figure 7 - Hydraulic restriction response

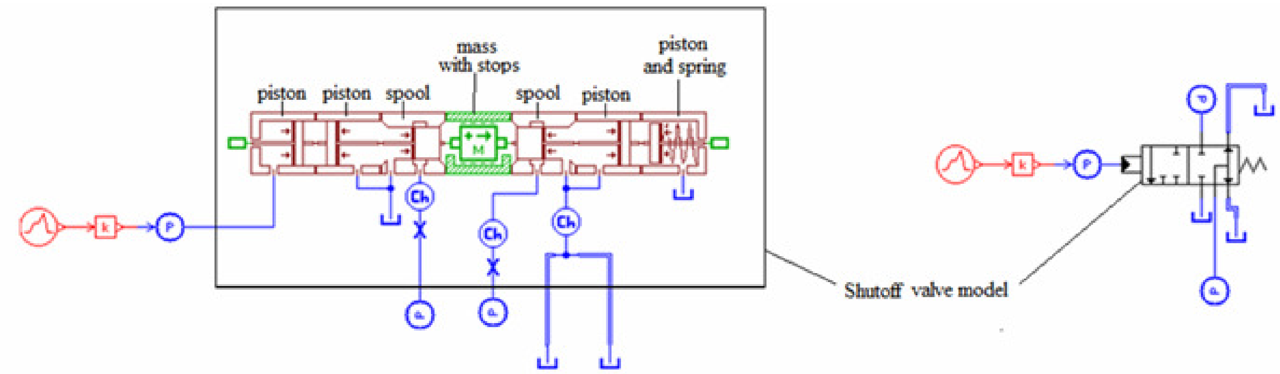


Figure 8 – Shutoff valve built with “Hydraulic Component Design” components

An important component to the correct representation of the systems real performance is the pressure source. To create the hydraulic pressure compensated pump model, using the AMESim “Hydraulic Component Design” library, the traditional signal flow modeling method was used. A power to signal flow converter was applied to switch a hydraulic port to a pressure and flow signal ports.

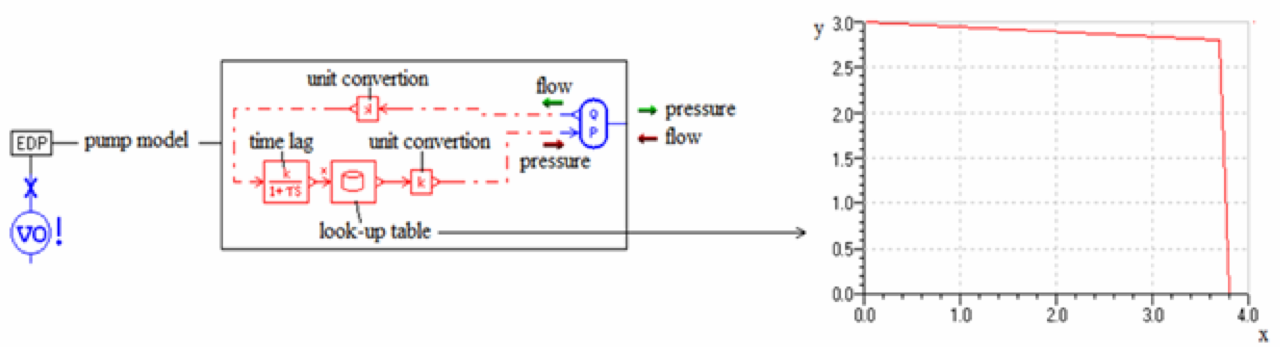


Figure 9 – Pump model on signal flow

The causality of this component is presented at Figure 9, where a flow signal value enters the loop, is treated by a unit conversion, enter a time lag that represents the pump`s compensating circuitry dynamics and searches for its respective pressure value, which is also converted to the appropriate unit and is available back to the same power to signal flow converter and to the hydraulic port connected to it.

### 2.3. Parameter identification

Even for the most studied and known systems, some parameters will always be of extreme difficulty to be mathematically determined. Friction coefficients are influenced by many factors and are determinant of overall system performance. A good way to reach a reasonable estimate of such parameters is confronting the model response with a real system response for the same input.

From the technical specification and qualification tests of the real components, all geometrical parameters used on the model are precise. Fluid characteristics and control logic implemented are also known and were introduced with fidelity.

Three parameters of the model had to be determined in a numerical optimization process: lumped system friction (Fatmass), pressure and return lines proportional orifice diameter (dpin and dpout). The first step in this direction is to simplify the complete model to a lighter one to require the least amount of computational processing. All secondary function valves had their functionalities removed and only a proportional restriction was assigned to them considering the position that they are kept on steering engaged mode.

Figure 10 illustrates the unknown parameters, which are the factor variables, localization (in balloons) and the implemented optimization function basis. The selected strategy is to impose a step angle position input on the control system and compare the wheel commanded response with a known real system response. To do so, a position versus time look up reference table is included in the model. The reference output of this table is then compared with the calculated wheel position response and the difference value is squared and integrated, resulting in the objective function Eq. (1) – the smaller the value of this result, the closer the system model is to reality.

$$obj = \int_0^{t} (reference - response)^2 \qquad (1)$$

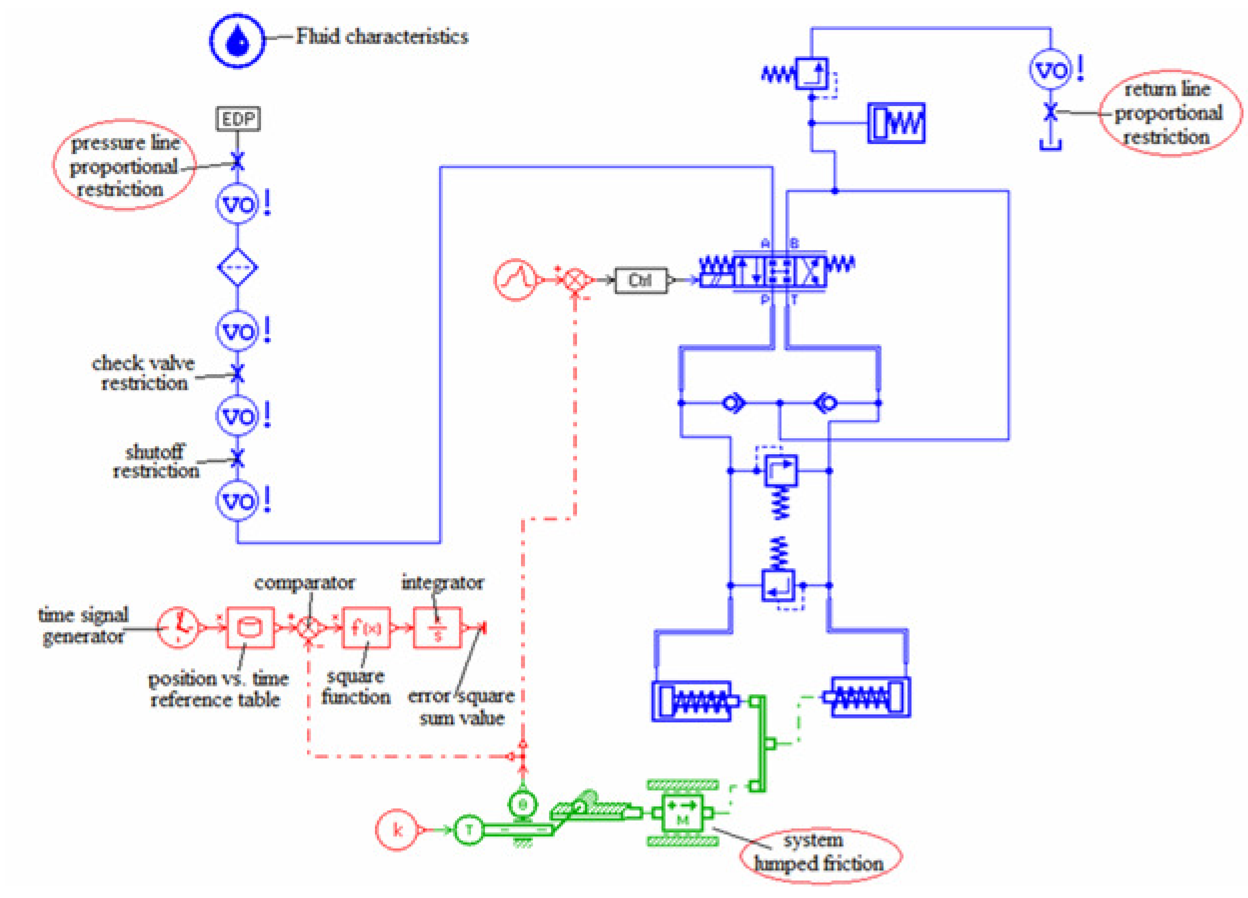


Figure 10 - Parameter identification model

Numerical optimization is used to minimize the described objective function, by imposing variations on the factor variables.

Diverse situations had to be analyzed to obtain a good result. From a single system step response, different combinations of the factor variables could be reached. This difficulty is mainly due to the resistance aspect that the variables have in common; a high friction may compensate a lower inlet restriction value, which could invalidate the model under different operational conditions.

To overcome this issue, four real system step response were obtained combining normal and cold temperature with loaded and unloaded system. Temperature was included on the simulation by applying temperature respective dynamic viscosity coefficient to the fluid, while load on the system is considered an outside torque, directly applied to the wheel shaft, opportunely against or in favor of the wheel movement direction.

An important point is that the parameter identification process has to be performed simultaneously to all situations, what turns the optimization into a four distinct objective functions (erro_no_load_normal_day; erro_load_normal_day; erro_no_load_cold_day; erro_load_cold_day). The best solution is the one in which the sum of these functions is the smallest.

Genetic algorithm was used to search for the best solution due to its ability to explore all the possible universe of parameters combination globally. Following the handbook recommendations (LMS Imagine, S.A. 2007), the numerical process parameters were:

- Population Size: 20
- Reproduction ratio: 65%
- Maximum number of generation: 15
- Mutation probability: 10%
- Mutation amplitude: 0.2
- Seed: 1

The evolution of the process can be seen in Figure 11, both entry variables and objective functions values. After 14 generations and 202 runs, the best solution found is below. Simulation with these parameters implemented results in Figure 12.

- dpin = 1.89
- dpout = 1.77
- Fatmass = 2.00e+006
- erro_no_load_normal_day = 1.59e+002
- erro_load_normal_day = 3.30e+001
- erro_no_load_cold_day = 9.60e+001
- erro_load_cold_day = 2.82e+002

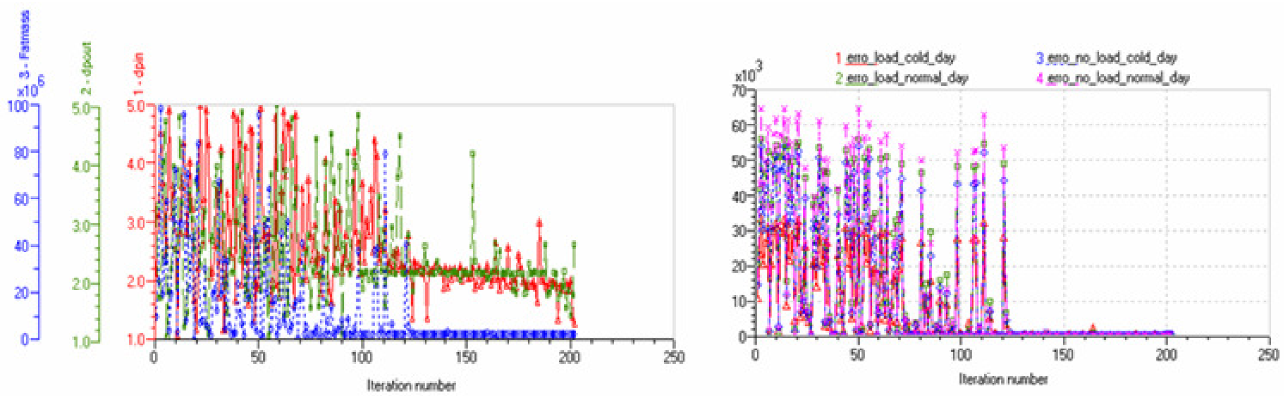


Figure 11 – Genetic algorithm based parameter identification

In order to check if the genetic algorithm method have reached a local minimum and if not, to reach it, a second optimization process was conducted for the same objective function and variable set using the gradient method (relative gradient = 1e-6; final accuracy = 1e-4).

With 9 iterations and 27 simulation runs, the algorithm completed successfully and converged to:

- dpin = 1.62
- dpout = 1.58
- Fatmass = 1.88e+006
- erro_no_load_normal_day = 1.54e+002
- erro_load_normal_day = 4.70e+001
- erro_no_load_cold_day = 1.74e+002
- erro_load_cold_day = 1.65e+002

The result is only slightly better than the previous one, with very little gain considering the sum of the four different situations error. See right hand graph at Figure 13, it attests that the first results had achieved a high level of accuracy. Since the systems did not present significant performance deviation, the graphs are not presented.

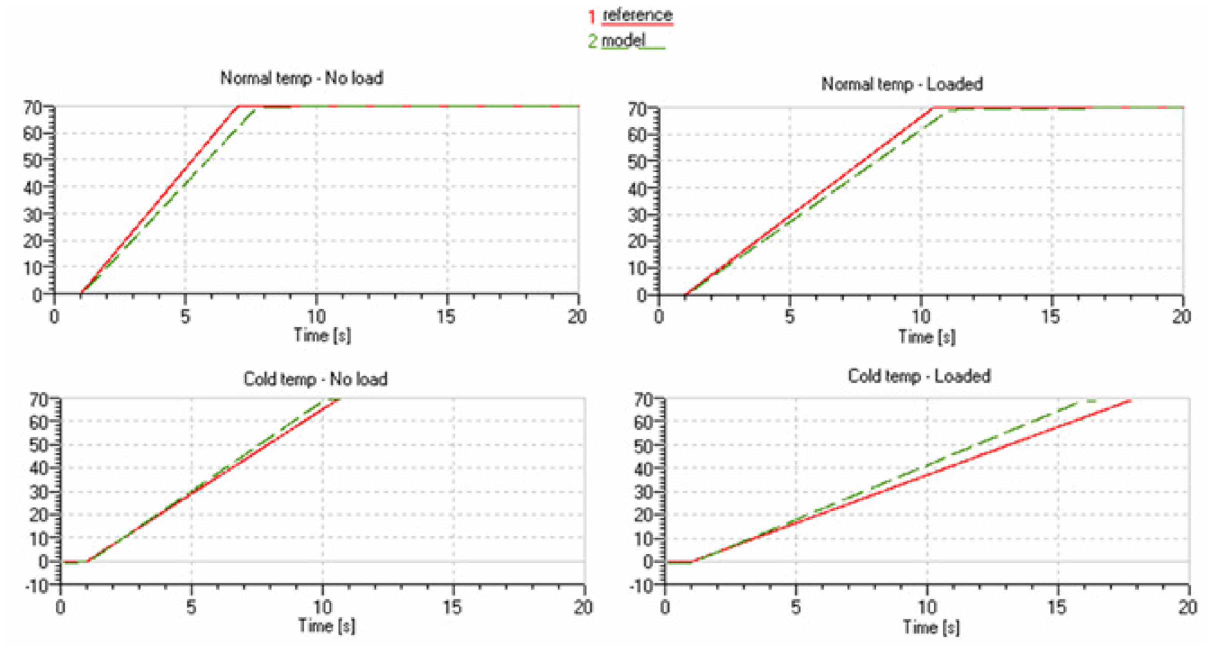


Figure 12 – System reference and model response

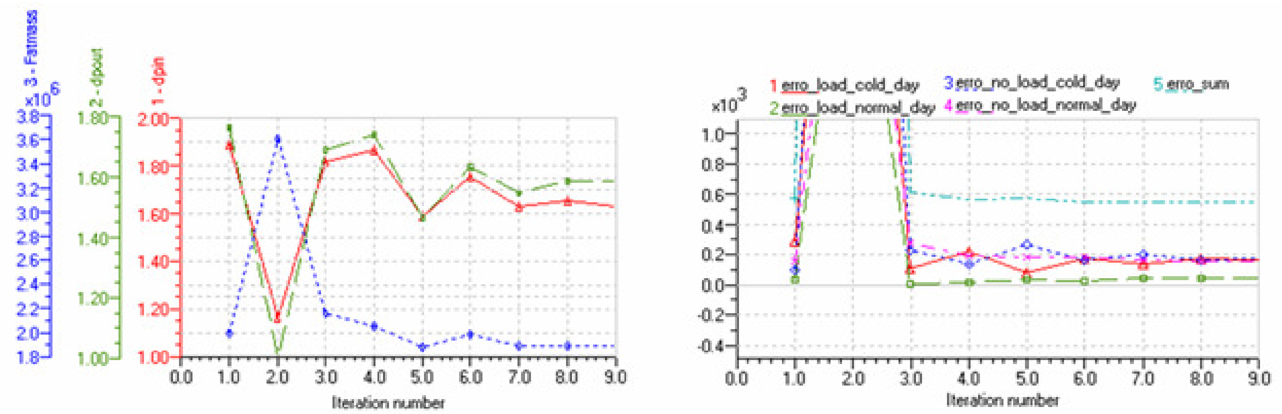


Figure 13 – Gradient method optimization process

## 2.4. Performance Optimization

From the above topic, the directional function of the steering system is modeled and have its parameters validated. Going on with this case, a parametrical study will be performed by systematically modifying input design variables and analyzing their influence to a response function. At this time, the control part of the model was once more adapted to reach the best objective function: error integral on Figure 14. It basically is comparing the system response to its input commanded signal. All other identified components on the up mentioned figure refer to the input parameters that will be analyzed. Dpin, dfilter, dcheckin, dbypass and dpout are proportional diameters to represent pressure drop. Cflow is the characteristic flow rate of the directional valve to a given pressure drop. Pdiam is the piston diameter and Fatmass is the system lumped friction. All these parameters are feasible to be physically modified by redesign of the components, the cost involved at this is not always the same and has to be analyzed along their impact on the performance.

Figure 15 shows the system input and response with the identified parameters. The response function is calculated when a step is imposed to the command, along with a torque load acting against its movement (negative value) and afterwards a step back to neutral position, this time with the torque load acting in the same direction as the movement. This last part is to consider the control ability to keep the system with no over travel.

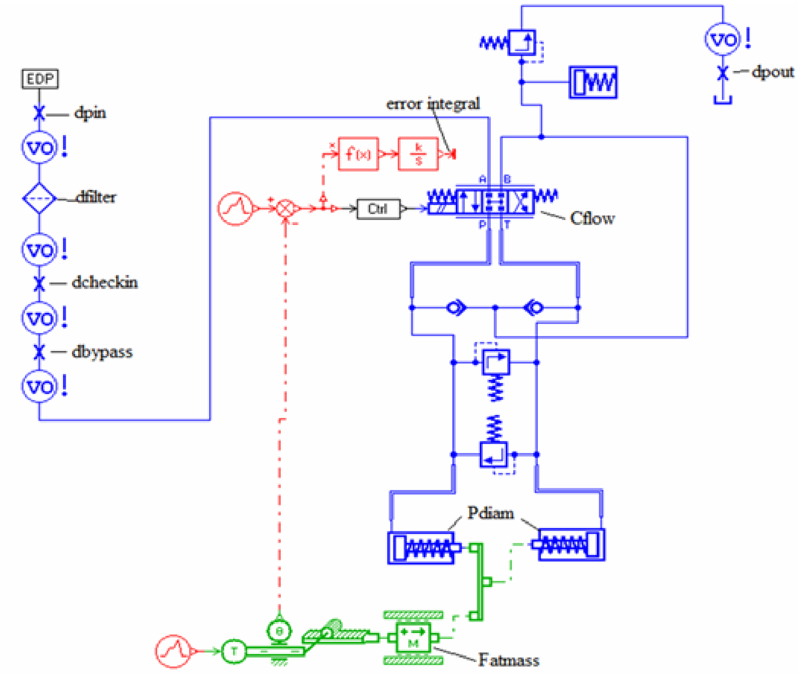


Figure 14 – Parametric study model

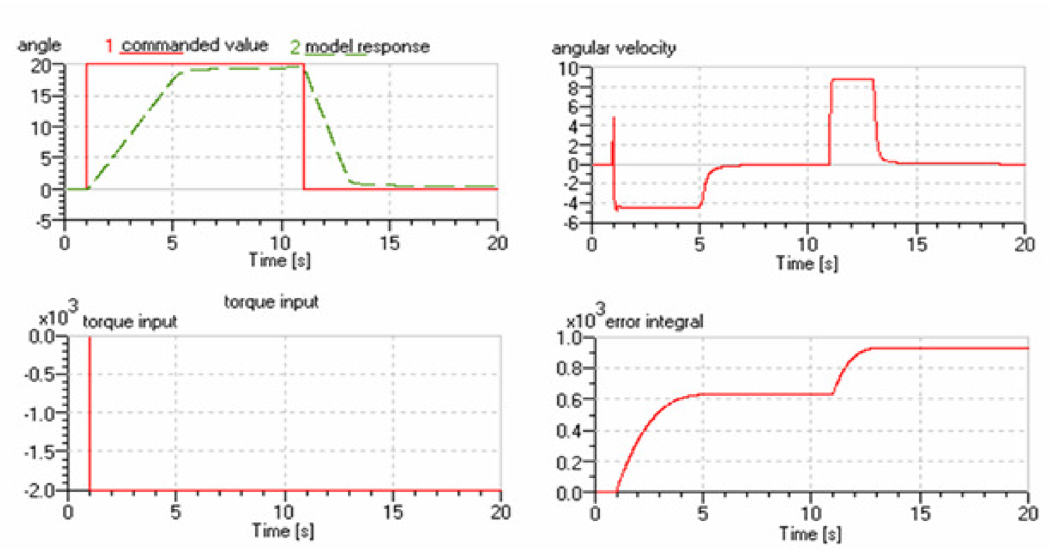


Figure 15 – Parametric model input and results

Full factorial method was applied on the problem resulting on 256 combinations of the parameters values, always varying among them by plus or minus 10%. The effect on the response function is presented on Figure 16 in percentage; all effects bellow 1% were not considered.

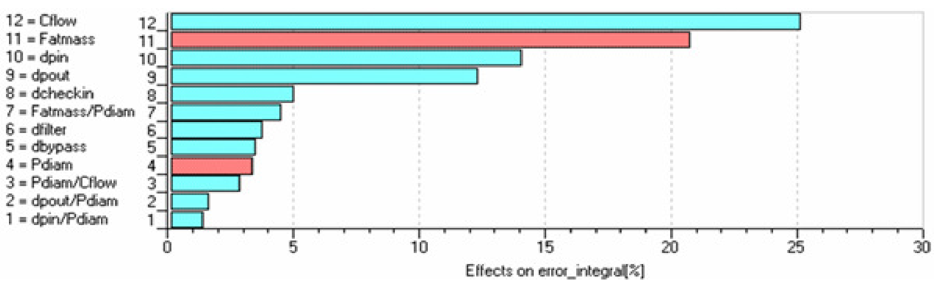


Figure 16 – Parametric study effect Pareto diagram

Considering the above results, the three most significant parameters were modified by 20% and the system was simulated once more. Figure 17 expresses the gain of this modification. Special attention is given to the angular velocity at the first actuation, which went from 4.3 to 5.3 engineering units, representing almost 25% gain on a very important performance criterion.

A recommended action that can be made to implement dpin and dpout modifications on the system is a design review of the hydraulic system generation and distribution routing to shorten it or by using lower friction or bigger diameter tubing. Cflow requires a hydraulic steering manifold redesign, either by smoothing fluid flow passages or by increasing the directional valve spool slots.

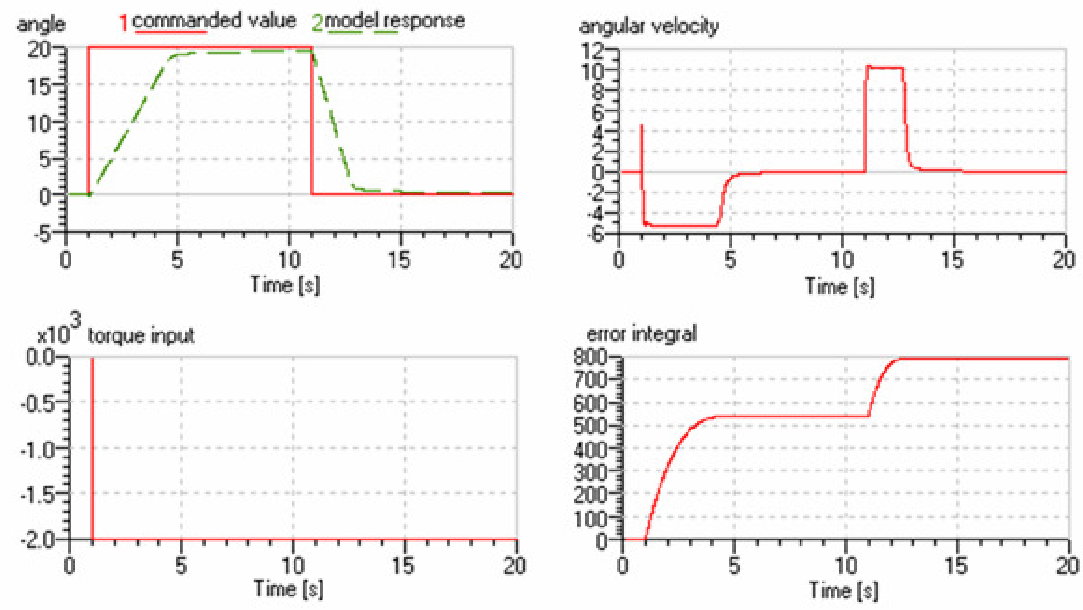


Figure 17 – Parametric model input and results after most significant parameters modification

## 3. CONCLUSION

The proposed modeling method was successful in representing the focused system dynamics. Parameter identification via numerical optimization is a powerful tool which had a very good result in combination to the physical phenomenon considered by each of the components model. As expected, optimization based on genetic algorithm was proven to be effective to reach objective functions global minimum while the gradient method was correct to locate local minimum.

The chosen computational tool AMESim have proved to be comprehensive enough to be a aid on system engineering, keeping up to its promise of allowing the engineer to be focused on the phenomena interaction between complexes system rather than on mathematical equations implementation.

Steering actuation speed performance improvement proposal is significant and is considered to be robust due to the fact that it has been done based on a validated system model.

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