CILAMCE
PANACM
RIO DE JANEIRO 2021

Modeling and simulation of an aircraft's hydraulic distribution system based on a LMS Amesim® Model and a Bond Graph support

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Abstract. This paper presents two different and complementary modeling techniques to analyze the main characteristics of hydraulic systems and identify potential failure scenarios. To assess the behavior of system relevant variables the LMS Amesim® was used and a dashboard was developed to enhance the post simulation analysis of the aircraft operation. As a study case, a typical commercial aircraft hydraulic architecture was modeled and some failure scenarios were studied, such as single engine failure during take-off, complete propulsion system failure during the flight, and also a normal landing operation. In parallel, a bond graph diagram representing the system components is developed as a support tool to provide a more detailed understanding of the modeled physics.

Keywords: Aircraft Systems, Hydraulic Systems, Modeling and Simulation, Amesim®, Bond Graphs

1 Introduction.

The aircraft's hydraulic system sets up an important role on larger aircraft. It maintains contact with different aircraft systems such as flight controls and landing gear [1]. A hydraulic system can be decomposed in different subsystems. One of the most important is the hydraulic distribution system that is responsible for managing the flow rate and pressure for the primary control surfaces such as ailerons, rudder, and elevator, secondary control surfaces such as the slats, flaps, and spoilers, and finally the landing gear system including the braking, steering and extension/retraction subsystems. The system has main components such as bootstrap reservoirs, accumulators, hydraulics pumps, and the Power Transfer Unit (PTU). This system must be robust and capable of maintaining the quality of aircraft's controls during normal conditions and diverse failure conditions.

When it comes to testing real aeronautical systems, investments in complex and expensive procedures are often applied [2]. One way to get around these requirements for preliminary assessments is through the use of computational simulations. Also, the capability of predicting the system behavior and potential failures has gained relevance in the aeronautical industry to improve the support troubleshooting processes during operation [3]. As a result, many modeling and simulation tools are becoming more frequently used in the aircraft's design.

This work models and simulates the architecture of the hydraulic distribution system of a typical commercial aircraft with Amesim®, a commercially available multi-domain systems simulation software. Likewise, bond graph diagrams representing the system components are presented and used as support tools to provide a more detailed understanding of the physics involved. Bond graphs are used to represent physical systems in an unified way, they are often used to describe complex systems as they easily correlates graphic energy representation into state-space representation [4].

2 Overview and methodology.

The aircraft hydraulic distribution system has the responsibility to feed all the hydraulic actuators of the aircraft. The main components of the distribution systems are the hydraulics pumps, bootstrap reservoir and PTU. This system main function is to provide flow for the main flight control surface actuators (aileron, rudder and elevator), the secondary control surfaces (slats, flaps and spoilers) and the landing gear system (landing gear extension, steering and brakes). In order to feed such a complex system, the distribution system is divided in three systems in order to have a better performance, safety and redundancy, as shown in Figure 1.

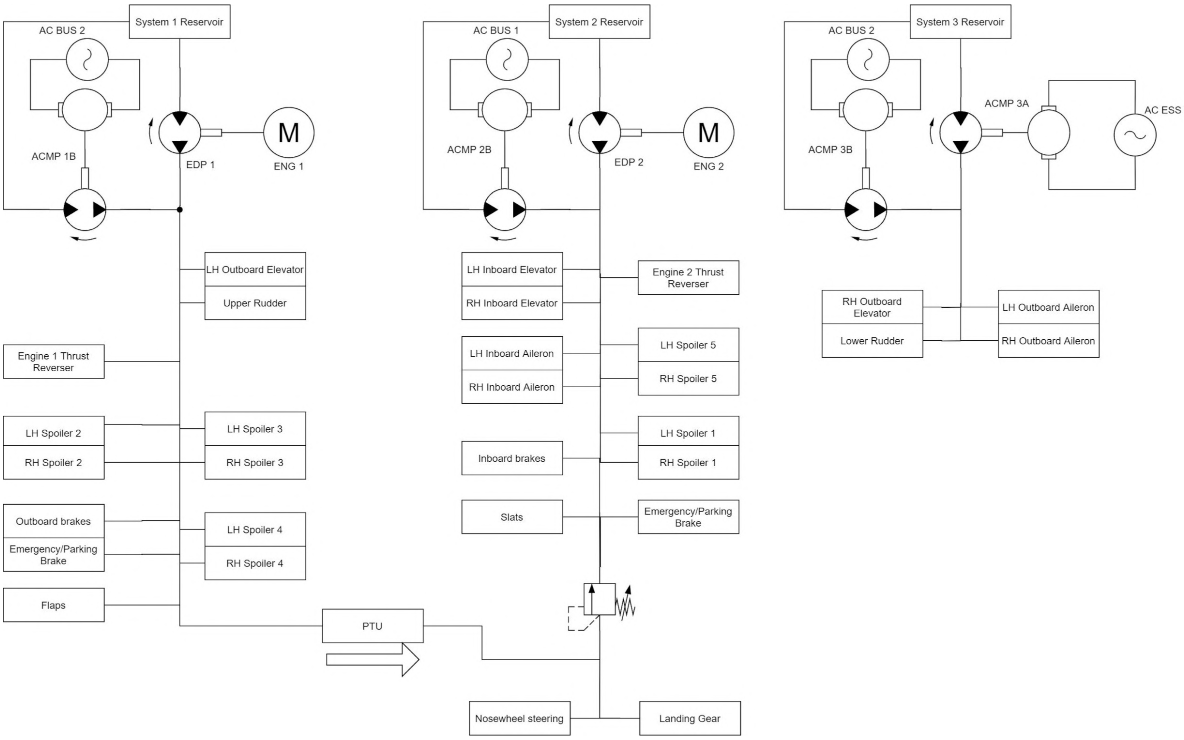

Figure 1. Aircraft hydraulic system considered architecture

In order to simulate failures conditions for this complex system, a Amesim® model was developed to perform numerical simulations utilizing the bond graph methodology to validate the physical and causality relation between the all of the systems components. The modeling overview is presented in Figure 2. The white blocks represent the Hydraulic Systems of components that receive the HP and LP (High and Low Pressures) lines that distribute pressure and power to the components described in Figure 1.

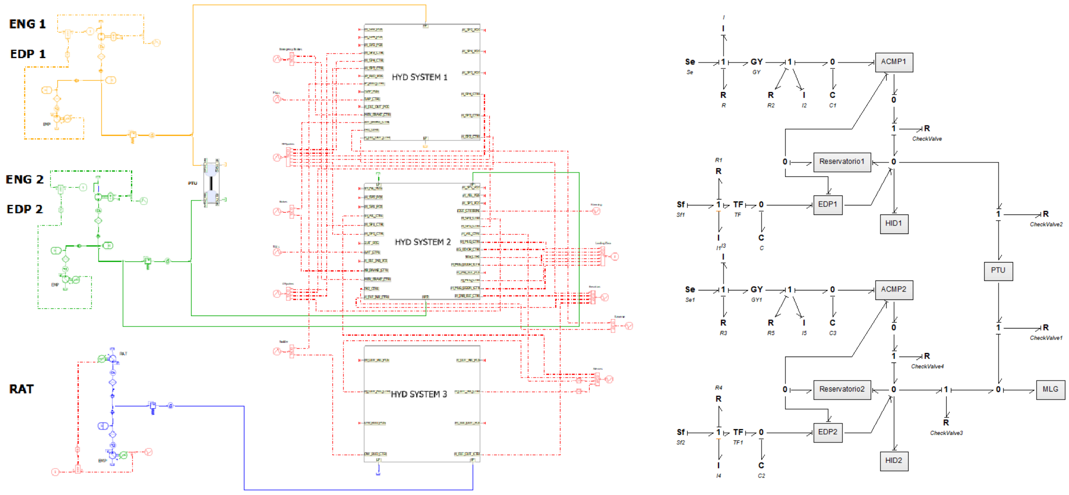

Figure 2. Aircraft hydraulic system Amesim model (left) and Bond Graph model (right)

3 Power Transfer Unit (PTU).

For larger aircraft it is important to have redundancy between critical systems in order to avoid hazard failures during its operation. Thus, the hydraulic feeding system has its redundancy through the Power Transfer Unit, a component capable of establishing a flow communication between the System 1 and System 2. In case of a problem on any of these systems, the working one is capable to continue feeding the components of the system with failure by utilizing the PTU. In Figure 3, it is shown the modeling of this component both on Amesim® and utilizing bond graphs.

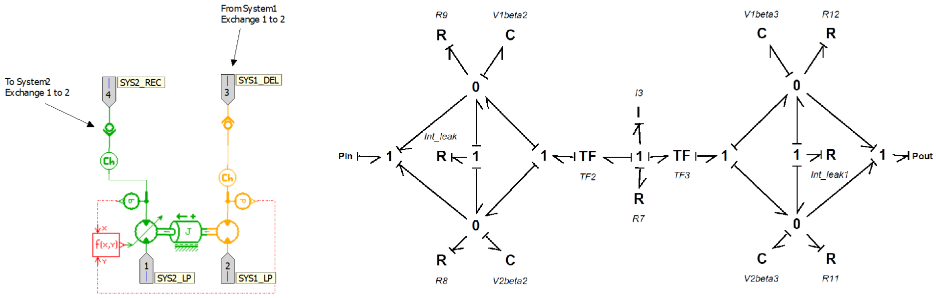

Figure 3. PTU Amesim model (left) and Bond Graph model (right)

In bond graph modeling its important to notice that the Resistances (R) represent flow leakage both for the exterior through the pipe connections and between the chambers interior. Capacitance (C) are applied to consider flow compressibility on the pump chambers. All of these characteristics are considered on the Amesim® model.

4 Engine Driven Pump (EDP).

The EDP is one of the main components of an aircraft hydraulic system. Coupled to the engine axis, the EDP is responsible to convert mechanical in hydraulic power. In the modeled system, the EDP is a variable displacement pump. This kind of pump is capable of maintaining nominal system pressures (up to a certain limit) by varying it's displacement [5]. Figure 4 shows the pump's schematic bond graph model. In the Amesim simulations, a standard component was used.

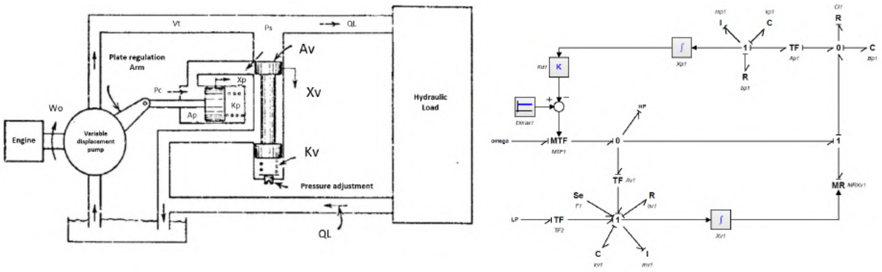

Figure 4. Variable displacement pump schematic (left) [6] and Bond Graph model (right)

The bond graph includes the mechanical feedback loops that guarantee the pressure control. The mechanical properties of the pistons involved in this feedback, such as mass, friction and spring rate are also modeled.

5 Bootstrap reservoir.

The main function of the bootstrap reservoir on the distribution system is to maintain the flow pressurized for some period of time even if the hydraulic pump fails, in order to allow a smooth transition for the PTU or even to maintain the components fed in emergency scenarios. The reservoir main components are the flow chambers and a piston connecting them. There are also check valves to avoid flow return and a relief valve to avoid high pressure in the low pressure chamber. The model was based considering the studies by [7]. It was modeled using only basic Amesim® hydraulic components, and its bond graph representation is also shown in Figure 5.

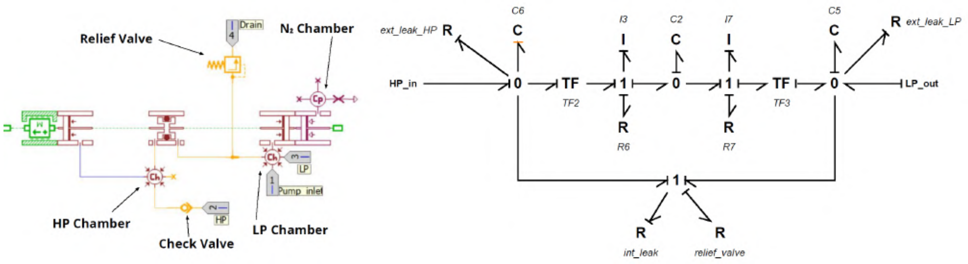

Figure 5. Reservoir Amesim model (left) and Bond Graph model (right)

6 Simulations.

The Amesim® model was simulated to assess the responses of the system to different inputs and failure scenarios. The main objective of the simulations is to verify and evaluate the activation and the interactions between the three hydraulic systems and the response of the main components for the different simulation cases.

The two simulations here presented are failure scenarios. In the first case, the 2 engines fail and the EDP's no longer generate pressure to the Systems 1 and 2, while System 3 has a normal operation. In this case, the implemented logic will activate the two main AC pumps to allow a minimum performance of the commands. This simulation tries to simulate two scenarios: a first case of losing the engines of the aircraft and how the backup pumps try to maintain performance; a second case of losing all the main pumps and electrical backup pumps, and how the RAT associated pump (mechanical, with a propeller to generate pressure) maintains performance of the primary flight controls surfaces commands, a case of ”black airplane”. The Simulation 2 aims to assess the loss of a whole hydraulic system, with failure of the EDP and the AC pump has a latent failure that not allows it to activate it. This case has main goals to assess the performance of the PTU, that must deliver pressure to the system 2, to maintain the performance of the commands, even with the the failed pumps.

6.1 Simulation of Failure Scenario 1.

In the first simulation, the 2 EDPs fail at $t = 10s$ and the ACMP3 fails at $t = 35s$. The flight control surfaces, brakes and reverse thrusts are commanded by a cyclic square wave to represent an intensive use of the hydraulic system. In Figure 6, the rudder, elevator, brakes and steering responses are presented. The angular responses are compared with the pilot's input (in red). In the first 10 seconds, the aircraft is in normal operation, then the EDPs fail simultaneously and the backup pumps are activated. These pumps have a lower performance than the EDPs, so they deliver a reduced pressure in the high pressure lines. In this case, the systems 1 and 2 are affected and the commands responses are gradually deteriorated. However, the system still responds to the pilots inputs, representing a minimum performance for the aircraft, that is adequate for a case of loss of all engines. The sizing of the backup pump is not covered in this paper, but it should be chosen to allow the lowest loss of performance. An important aspect is that the system 3 has a failure only in $t = 35s$ and has slight losses of performance, also related to the sizing of the RAT AC pump. In the case of the brake command force, the loss of the EDPs also affects the braking performance, as the force generation depends on the activation of EHSVs (Electrohydraulic servo valves).

To analyse the hydraulic performance, the Figure 7 presents the pressure and flows rates of the three systems, through the High Pressure (HP) lines, the EDPs and the AC backup pumps. In this case, it is possible to observe that until $t = 10s$, the systems 1 and 2 have normal pressure lines, up to 3000 psi, the maximum system pressure. The flow rates through the EDP is variable with the fluid consumption with the input commands. When the EDPs fail, the flow rates through them reduces to zero and the AC backup pumps start receiving flow through them, to compensate the loss of the engines, however with a reduced flow rate, as discussed previously.

The RAT AC back pump is activated in $t = 35s$ and responds in a similar manner than the systems 1 and 2 EDPs failures. In this case, the HP lines pressure is also because of the sizing of the RAT AC backup pump, as discussed earlier. An important aspect of the these hydraulic systems is the response of the bootstrap reservoir and how they react to the failure scenarios. In Figure 8, the main parameters of the simulation related to the reservoir are presented: the pressure in the chambers (Low and High Pressure) and the displacement of the piston in the reservoir. In this simulation, is it possible to notice that in $t = 10s$, the reservoirs of systems 1 and 2, react to the reduced pressure generated by the AC backup pumps and they try to increase the HP pressure lines to compensate this scenario and maintain a minimum performance of the commands.

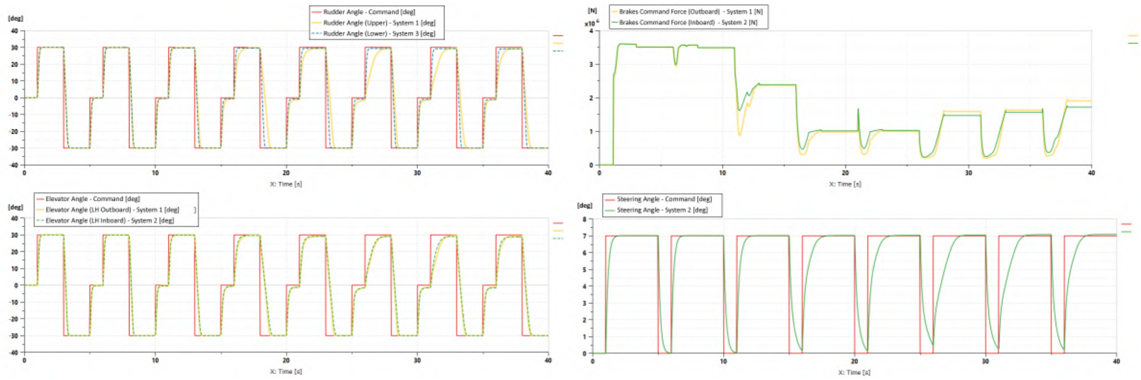

Figure 6. Responses of a set of primary control surfaces and secondary commands of the first simulation

Figure 7. Hydraulic systems pressures and flow rates of the first simulation

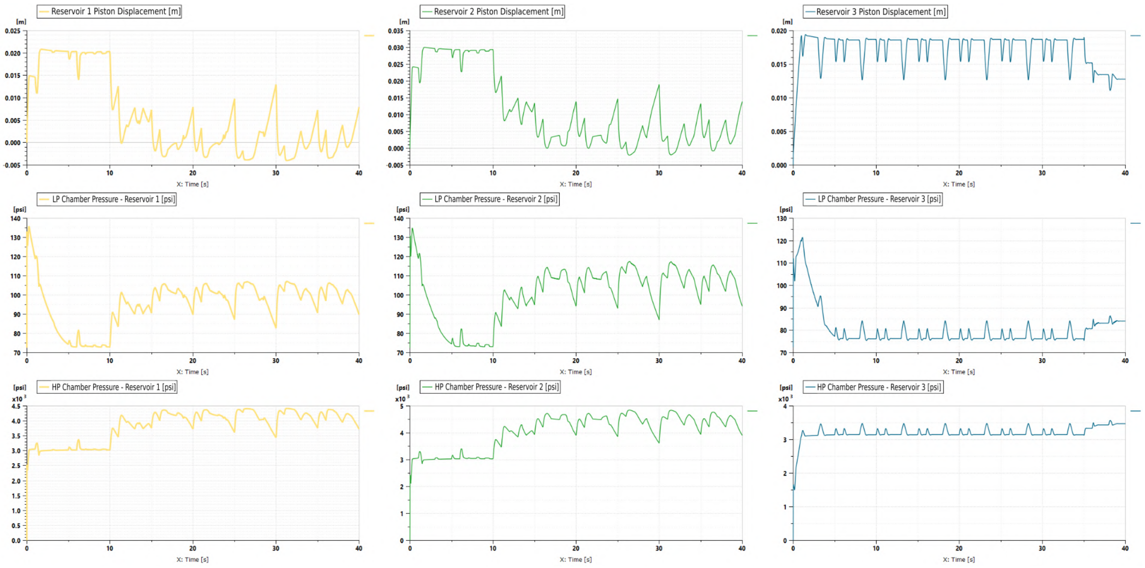

Figure 8. Response to the failures of the bootstrap reservoirs

6.2 Simulation of Failure Scenario 2.

In the second simulation, the EPD of the system 2 as well as the ACMP 2 fail at $t = 20s$. In this scenario, the system 2 capacity of pressure generation is lost, and the PTU ans the reservoir are responsible for obtaining a minimum system performance. In Figure 9, the same response variables are presented as a manner of comparison with the first simulation. In this case is noticeable the capacity of the PTU and the bootstrap reservoir, as the loss of command performance is minimum, with greater differences in the case of the braking performance. The system 2 remains with great capacities of response, because one EDP can handle the responses of 2 systems simultaneously.

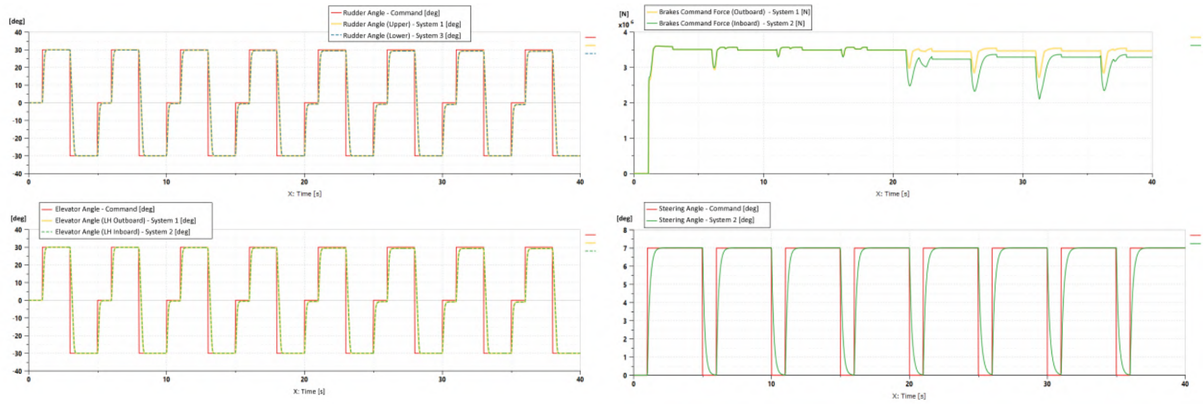

Figure 9. Responses of a set of primary control surfaces and secondary commands of the second simulation

The PTU, in this model, is considered unidirectional, so its energy transfer capacity is only from system 1 to 2, as presented in Figure 2. In Figure 10, the pressure of inlet and outlet ports of the PTU are presented, and it is possible to notice that the actuation of the PTU starts at $t = 20s$, when the failure scenario starts.

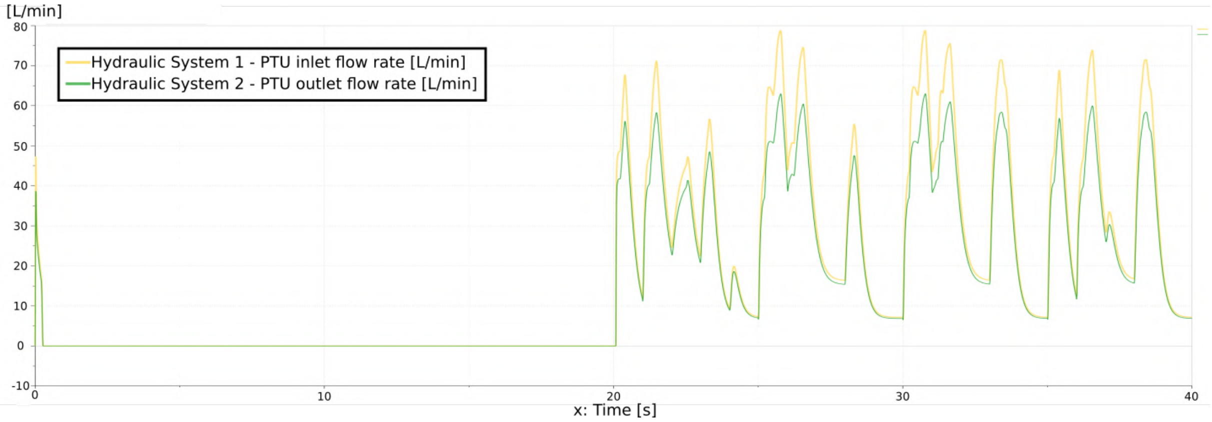

Figure 10. Power Transfer Unit flow rates of the second simulation

In Figure 11, the same variables of the hydraulic systems are presented. In that manner, the flow passing through the EDP 2 reduces to zero in $t = 20s$ and the ACMP is not activated as the failure scenario includes a latent failure of the backup pump.

In this case, it is possible to observe that the system 1 is slightly affected with the failure as the PTU shares the sources of pressure between the two systems. However, for the system 1, this slight reduction of pressure in its HP lines does not alter the performance of the commands related to this system. For the system 2, the pressure through the HP lines is affected to the new mode of operation, exclusively through the PTU and bootstrap reservoirs. In this case, it is possible to observe, that the PTU can generate enough pressure to allow the commands in system 1.

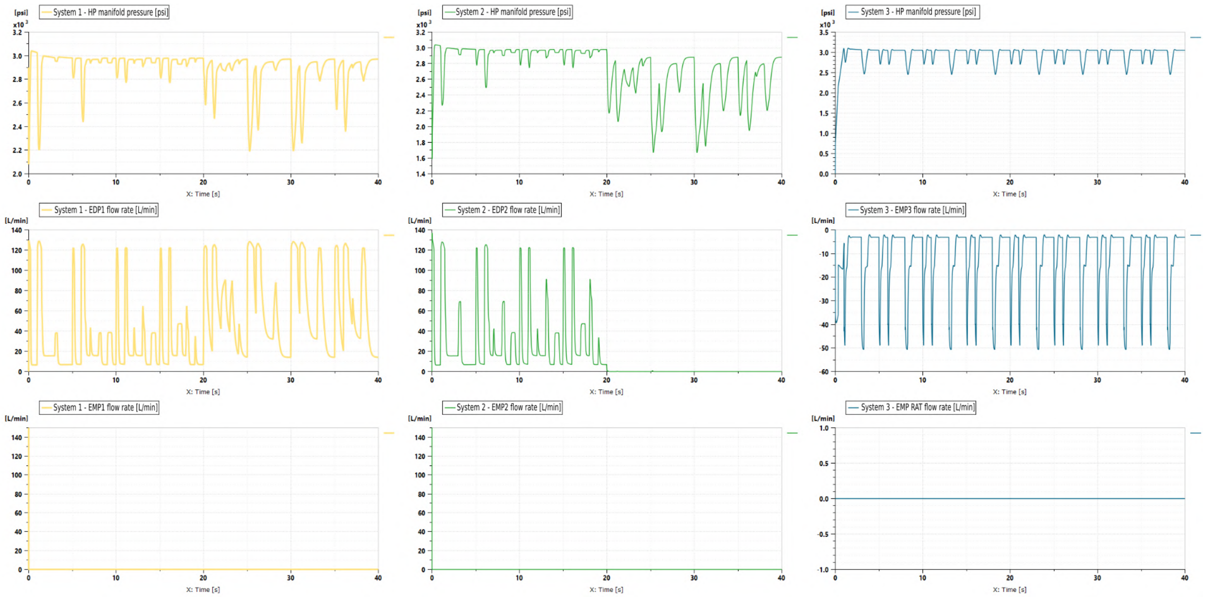

Figure 11. Hydraulic systems pressures and flow rates of the second simulation

7 Conclusions.

The target of the analysis and the simulations is the integration and interfaces between systems and the main components. The three systems and their architectures presented robustness in the failure scenarios and responded appropriately to them. This models can be adapted to different aircraft and help to assess different real-life situations, including with possible hardware in the loop for assessing the real components in the systems architecture logic.

Amesim® proved to be a powerful tool for modeling and simulation of complex systems in a rapid and visual way. The built-in components simplify the modeling process and can be used for the construction of more complex ones. On the other hand, bond graphs give a more profound understanding and control of the modeling physics, with the drawback of of adding complexity to the process. It's important to highlight that simulations can also be made with this kind of model. The tools are then complementary and well suited for the development and analysis of complex systems, such as aircraft hydraulics.

Authorship statement.

The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

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