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A BOND GRAPH-ORIENTED METHOD FOR ASSESSMENT OF FAILURES IN AN AIRCRAFT HYDRAULIC BRAKE SYSTEM

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Abstract

In the context of system failures analysis, the present work aims to demonstrate the benefits of working in a cohesive manner with two particular modeling techniques, a physical modeling-based computational software and the bond graph concepts, when identifying failure modes and assessing the impacts of typical failures in an aircraft hydraulic brake system. The brake system performs an important, safety-related function in aircraft operation.

1 Introduction

Due to the increase of aircraft systems complexity along the decades and the continuous improvements done by the regulatory authorities on the certification basis requirements for safer operations, the safety assessment accomplished by systems engineers has been demanding more effort from the specialists to make a complete, deep evaluation of the system and respective interfaces as a whole. Moreover, the capability of predicting the real effects of components failures in the system behavior in order to make better assessments of their severities and to support effective troubleshooting processes during aircraft operation has also represented a challenging activity. In that context, the development of computational models and subsequent simulations have become a common practice in the aeronautical industry.

Among the several modeling methods applied nowadays, the present work aims to demonstrate the benefits of working in a cohesive manner with two particular modeling techniques: a physical modeling-based computational software and the bond graph concepts. By means of the connection of physical blocks representing full component properties or just some relevant dynamic effects, the physical modeling software allows the accomplishment of quick assessments of system behavior on different conditions and provides flexibility for performance evaluation when architecture modification is implemented or component failure is simulated. On the other hand, the bond graph approach comprises a modeling method that allows a visual representation of the main dynamic effects and the energy interactions within the system, providing to the designer a better understanding about the several points of energy dissipation, preservation and type conversion throughout it.

1.1 Modeling and Applications

The current availability of computational resources and the subsequent use of simulation modeling have facilitated the execution of the so-called ‘concurrent engineering’, essential for the reduction of system development cycles as well as for the prediction of future system operational problems. Characterized by the incorporation of product lifecycle values into its initial design phases, the concurrent engineering has been supported in the industry by the benefits associated with the use of computational models, multidisciplinary analyses and optimization tools [1][2].

Moreover, there is a rigorous and important activity during the aircraft system development process called 'safety assessment', which consists in an iterative methodology to evaluate, by means of qualitative and quantitative aspects, if the impacts associated with the system failure modes were properly addressed in the course of its design. Nowadays, complete and well-organized processes like the ones described in ARP4761 [3] are commonly applied when developing the safety assessment of aircraft airborne systems and equipment.

However, the methods related to the system safety assessment process comprise manual, laborious activities that have intrinsically a certain degree of difficulty. In addition, due to their subjective character, which relies on the experience and judgement capability of the engineer, the resultant analyses could be incomplete, incoherent or even present some errors. Therefore, the concept of model-based safety analysis (MBSA) has been studied and started to be applied more frequently in the last years [4][5].

The model-based fault detection and diagnosis (MBFDD) represents another concept that deals with system failure and takes advantage of the benefits of its modeling. Making use of mathematical models to help the detection of failures in systems, several techniques of this model-based approach have been studied since 1990s, like the ones described in [6] and [7].

1.2 Proposed Method

Aiming to represent a simple, complementary approach for identification and quick evaluation of the failure modes present in an aeronautical system, the method proposed herein for system behavior assessment in normal and faulty conditions is illustrated in the flow chart of Figure 1.

The method starts with the development of both models: the parameterized model of the system in a physical modeling software, herein applied the LMS Amesim®, and the equivalent bond graph diagram of the system, representative of relevant dynamic effects. While the computational model is validated based on available data and applied for the execution of simulations in nominal conditions, the main dynamics effects identification and the energy concept behind the bond graph diagram are used as a background for the prediction of the effects of typical faults in system performance. Next step is the selection of those failures of interest to be implemented in a faulty version of the physical model. Since the introduction of failure effects in the LMS Amesim® model comprises an easy task, the comparison of system behavior, once the simulation results of both nominal and faulty models are available, is straightforward. Finally, the main conclusions of the present process can be used to support the definition of system fault isolation procedures for field operation or to identify the necessity of taking some particular actions still during the product development phase, like the implementation of a monitoring system, the inclusion of a dedicated task in its maintenance plan or even a complete system redesign in order to reach a predetermined safety level.

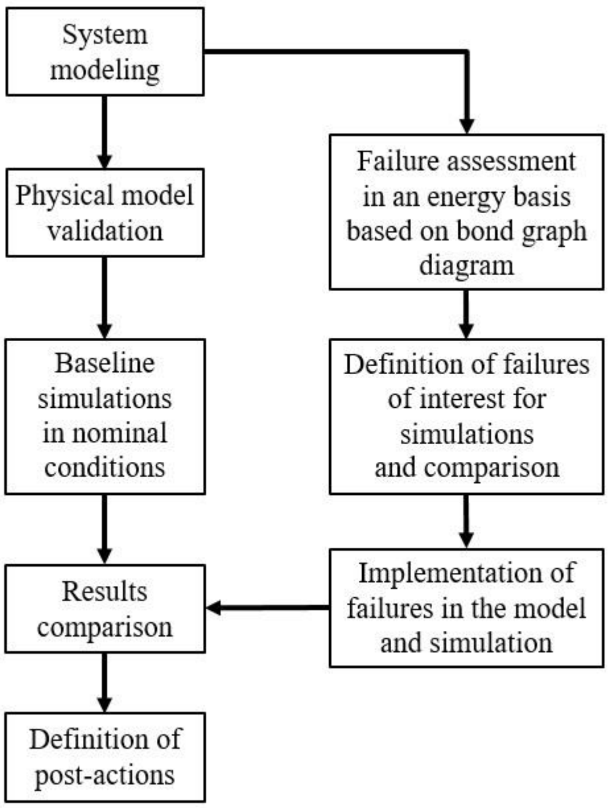

Fig. 1. Proposed method for system behavior assessment in normal and faulty modes.

1.3 Physical Modeling

The physical modeling available nowadays in computational software like the LMS Amesim® (Advanced Modeling Environment for Simulation) allows the development of multi-domain system models without the time-consuming duty of writing the dynamics equations and solving them.

By means of the interconnection of blocks representative, in a lumped manner, of system dynamic effects or full components, the LMS Amesim® constructs the system model through a multi-port approach, according to the intrinsic formulation associated with each physical block and respecting the generalized continuity laws.

The several libraries provided in the LMS Amesim® [8] help the engineer to find the most suitable block or the elementary ones to be combined to adequately model the system components. Mechanical, signal and control, hydraulic, ports and simulation are some examples of the libraries applied in the present work.

1.4 Bond Graph Modeling

Created in 1959 by professor Henry Paynter of Massachussetts Institute of Technology (MIT), the bond graph modeling technique consists in a compact graphical representation of the energy interactions within the system, which can be later applied for the construction of simulation models [9].

The bond graph modeling method has the benefit of allowing a clear, visual representation of the main dynamic effects present in a multi-domain system. Based on energy handling principles, the bond graph diagram is constructed applying bonds, junctions and elements to demonstrate how power is transferred throughout the system.

The bonds comprise arrows representative of the local instantaneous power, which is given by the product of its two associated variables: the 'effort' and the 'flow'. The application of generalized continuity laws at some system locations is guaranteed in the bond graph model by means of the use of '1' and '0' junctions. Those items denote, respectively, points of common flow variable and common effort variable, for those bonds attached to the respective junction.

Lastly, several elements are required in the bond graph technique to describe the way energy is handled inside the model. Flow and effort sources, dissipators, effort and flow stores, transformers and gyrators are the main dynamic elements employed in the construction of a system bond graph model.

2 Brake System Modeling

The brake system performs an important, safety-related function in aircraft operation. The system is responsible for not only decelerating the vehicle during a landing stop or a rejected takeoff, but it can also be applied to assist the speed control when taxiing, to park the aircraft, to improve ground handling due to differential braking and to halt wheel rotation at landing gear retraction. Brake systems are mostly supplied by hydraulic power in recent commercial and military aircraft.

The brake system design, architecture and functionalities have evolved through the years and the development of the antiskid system, part of the brake system of several aircraft since 1940s, comprised an important milestone in aircraft brake system history. The main function of the antiskid system comprises the prevention of a wheel locking condition, therefore, avoiding excessive tire wear and reducing the risk of a tire blowout [10].

The schematics of the hydraulic brake system applied as case study in the present work is shown in Figure 2. It consists in the system of a variable-sweep-wing fighter, whose technical information and test results have been published in [11][12] in the end of 1970's. As described in the figure, the 3,000-psig pressure is supplied by the aircraft hydraulic power generation system and later duplicated to each brake assembly, in which an independent hydraulic accumulator is installed to allow brakes application in emergency conditions or with the main hydraulic system turned off. The two-stage antiskid valves, one for each brake assembly, and four metering valves, commanded by the pilots through the brake pedals, are located inside a unique valve manifold [12].

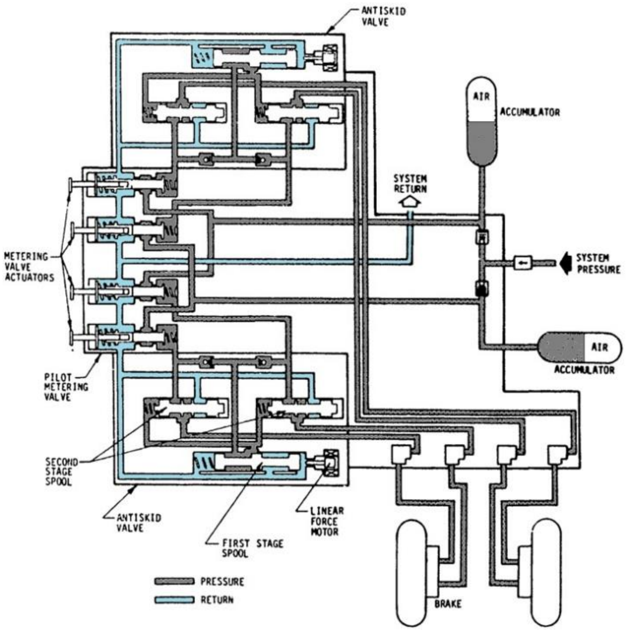

Fig. 2. Hydraulic brake system schematics. Source: [12]

The antiskid system of the aircraft is of the second-generation type, typically referred to as a 'quasi-modulating' system. Basically, the derivative of the wheel speed signal is compared to a threshold and, when it is exceeded, a control signal proportional to the deceleration error, plus any signal from the pressure bias circuit, is applied to release the brake pressure. The pressure bias circuit is an internal functionality responsible for the definition of the brake pressure reapplication manner in order to avoid another subsequent wheel skid condition [12].

2.1 Physical Model

The complete diagram of the physical model created in LMS Amesim® for the brake system and its interfaces is provided in Figure 3. The main elements of the hydraulic brake system can be found in the center of the figure, which are described by the valve manifold block, the brake assembly blocks, tubes, hoses, accumulators and an external check valve. A pressure source element and a tank element are used to represent the hydraulic pressure supplied by the aircraft generation system and the system reservoir, respectively. The antiskid system logic is included in the controller block, present at the bottom of Figure 3. The remaining blocks in the diagram consist in the system inputs, which are related to the brake pedals deflections, and in the main dynamics that play a significant role in the brake system performance: the braking dynamics, associated with the tire behavior and the dynamics of the wheel in contact with the pavement, and the airframe dynamics, comprising a combination of landing gear dynamics and the aircraft dynamics when subjected to the flight and ground loads.

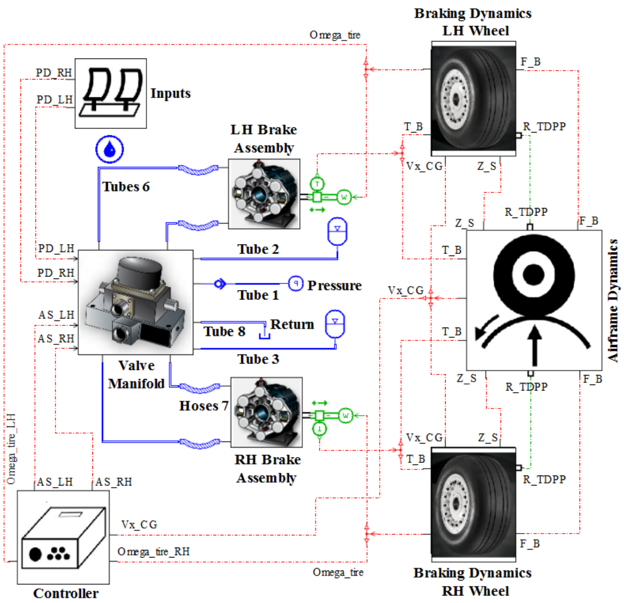

Fig. 3. Complete physical model.

The present work focuses on the hydraulic command of the brake system. Therefore, the physical model of the valve manifold is described in Figure 4. In a simpler configuration than the one shown in Figure 2, several 2-position, 3-port hydraulic valve elements of LMS Amesim® hydraulic library are applied to model the metering valves and both stages of the antiskid valves. With electrical operation and return by spring, the actuation signals of the metering valves and the 1st stage of the antiskid valves are supplied by the block representative of the system inputs through dimensionless connections of signal type. Due to the 2nd order intrinsic dynamics of the valve element, no feedback is assumed in the 1st stage of the antiskid valve.

On the other hand, a simplified model for the 2nd stage of antiskid valve is used in the physical model as detailed in Figure 5. Composed of fixed hydraulic orifices, simple hydraulic chamber elements and an internal loop between the output pressures of the 1st and 2nd stages of the antiskid valve to define the pilot pressure of the 2nd stage, the present model also applies the gains associated with the pressure sensor elements to weight the actuation area of each pressure on the feedback control.

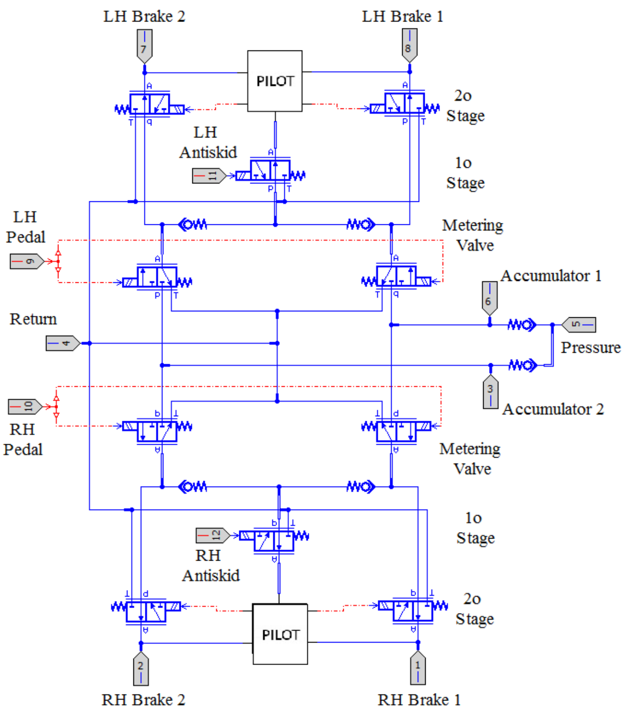

Fig. 4. Valve manifold physical model.

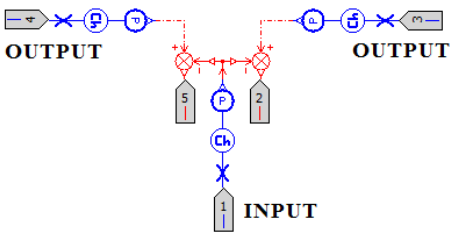

Fig. 5. Pilot control of antiskid valve 2nd stage.

Finally, the check valves located inside the valve assembly are straightforwardly modeled in Figure 4 by the spring-loaded check valve element of the LMS Amesim® hydraulic library.

2.2 Model Validation and Simulation

The validation process is a relevant step after the development of a mathematical model, whose purpose is to confirm the representativeness of the simulated behavior with respect to the one found in the real system. Once the physical model is validated, it becomes useful to predict the system performance in different operating conditions or even during abnormal situations like in the presence of faults.

In the aeronautical industry, the results of tests executed in a system laboratory rig, during the component qualification phase or in a full-scale aircraft are examples of sources typically applied to obtain data for simulation models validation. However, the literature is also an important data resource and the results of the tests provided in [11][12] for the fighter aircraft brake system under study were applied herein to validate the developed integrated model.

As described in Figure 6, the validation process was accomplished following a sequential approach, which started with the brake assembly and proceeded with the hydraulic system, the braking and aircraft dynamics, and concluded with the validation of the controller for two different operating conditions, that is, a dry runway and a wet runway. An amount of 147 parameters, of a total of 221, needed to be identified through the validation progression.

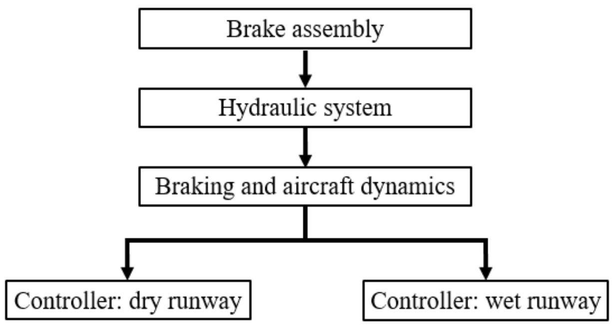

Fig. 6. Sequential validation approach.

The results of the complete validation process can be found in [13]. However, some variables of brake system performance in a dry runway operation are shown in Figures 7 and 8.

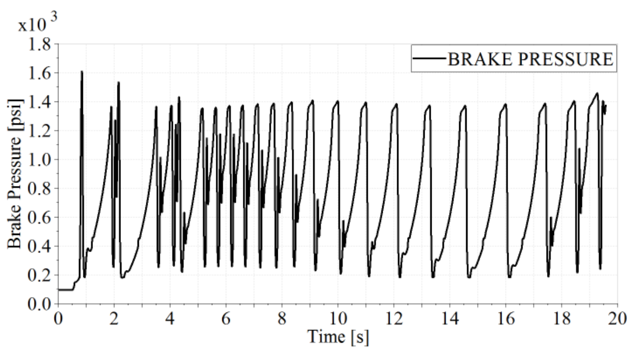

Fig. 7. Brake pressure: dry runway.

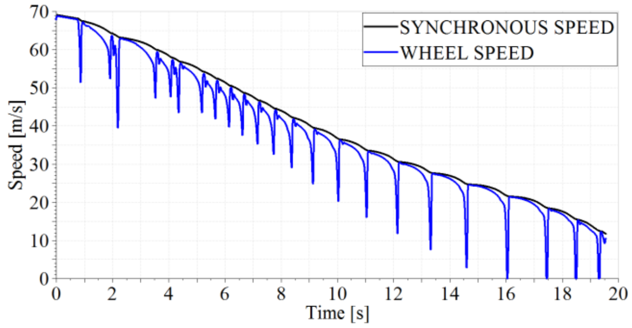

Fig. 8. Aircraft and wheel speeds: dry runway.

While the first graph describes the brake pressure profile throughout the aircraft braked stop, a comparison between the synchronous speed of the aircraft and the tangential speed of one wheel is depicted in the second graph. Those results are typical of a quasi-modulating antiskid system.

2.3 Hydraulic System Bond Graph Model

An equivalent, simplified bond graph diagram of the physical model of the hydraulic portion shown in Figure 3 can be created as illustrated in Figure 9. Due to the symmetry of the architecture, a part of the diagram is only indicated, but not represented on it.

While pressure sources (Se elements) are applied to model the hydraulic pressure provided by the aircraft generation system and its reservoir, hydraulic capacitances (C elements) are used in the diagram to portray the system accumulators. Although the physical model of the external check valve installed in the pressure line includes its transient effects, they are not taken into consideration in the model of Figure 9. Therefore, a hydraulic resistance (R element) is solely used to describe its pressure drop.

Regardless of the number of nodes adopted in the physical model for the system tubing, the main dynamic effects of the flow through the tubes and hoses are represented in Figure 9 by a simplified unique node, composed of a hydraulic resistance (R element) and a hydraulic inertance (I element), linked to a 1-junction, and a hydraulic capacitance (C element) linked to a 0-junction. Moreover, an effort source (Se element) is joined to the latter in the hose model to make the connection of the present diagram with the brake assembly ones. Lastly, full-arrows are attached to the valve manifold to represent the control commands to the brake system (brake pedals and antiskid controller signals).

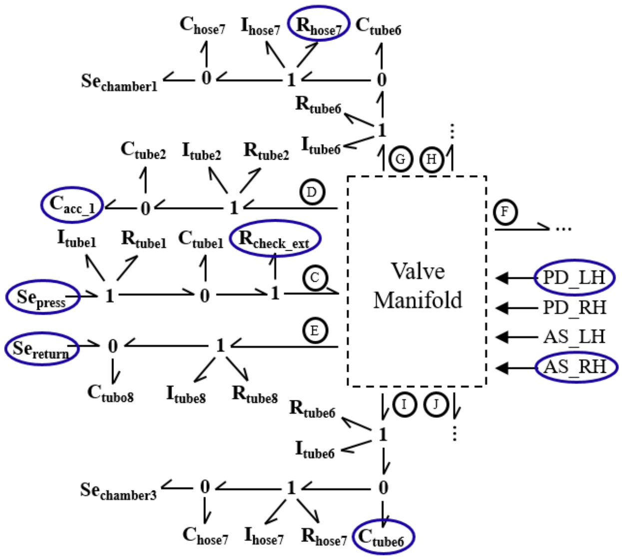

Fig. 9. Bond graph model of hydraulic system.

Figure 10 presents the bond graph diagram of the valve manifold. Again, some branches are omitted for simplification due to the symmetry of its interior. Circled letters and ellipses are used to denote equivalent branches.

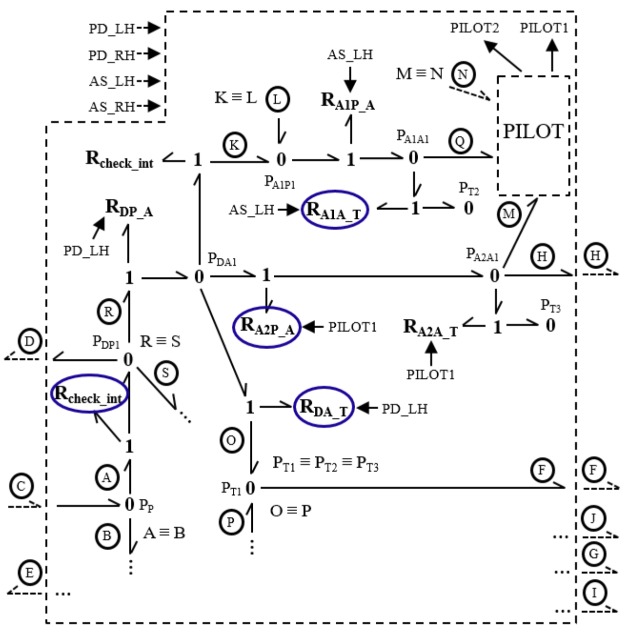

Fig. 10. Bond graph model of valve manifold.

Although the physical model depicted in Figure 4 considers the transient effects of each valve actuation, the equivalent bond graph of Figure 10 models the valve dynamics only by its pressure drop, represented by variable hydraulic resistances (R elements), whose control signals can be provided by the system inputs (brake pedals), by the antiskid operation or by internal stage pilot command. Similar to the external one, the internal check valves are uniquely described by their hydraulic resistances (R elements). Moreover, those common-pressure points inside the manifold are modeled applying 0-junctions, while 1-junctions are employed to denote points of pressure difference.

The pilot control of antiskid valve 2nd stage shown in Figure 5 is reproduced in Figure 11 in a bond graph format. As it can be seen, hydraulic resistances (R elements) are used to describe the flow resistance resultant from the inlet orifices, while the dynamic effect associated with any internal chamber volume is modeled by a capacitance resistance (C element).

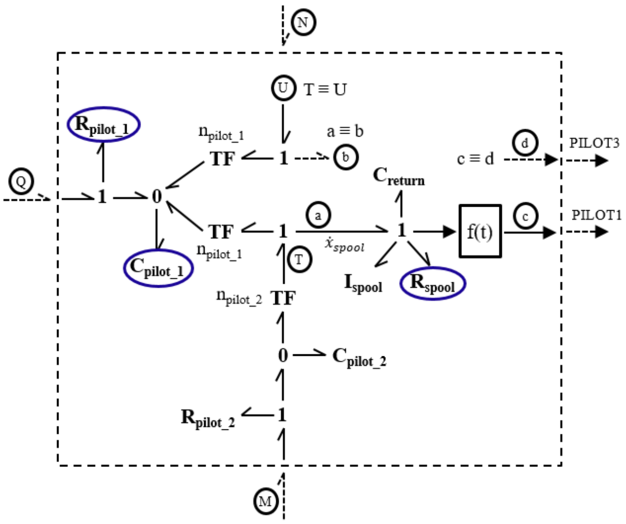

Fig. 11. Bond graph model of pilot control.

The bond graph representation of the antiskid valve 2nd stage pilot control in Figure 11 presents in detail the second-order dynamics of LMS Amesim® hydraulic valve as well as the forces equilibrium of Figure 5. Therefore, the balance of forces acting on the spool is modeled by 1-junctions and ideal transformers associated with the respective pressure areas. The spool mass, viscous friction and the return spring effects are depicted by mechanical elements of inertance (I element), resistance (R element) and capacitance (C element), respectively.

Finally, the relationship between the pilot subsystem output and the spool velocity is described by means of active bonds and a block representative of a generic, temporal function. Since the pressure drop across a servovalve is normally a function of the passage area given by the spool position, the respective *f(t)* function may simply denote the time integral of the spool velocity.

3 Failure Assessment

Several structured methods like the ones described in ARP4761 [3] are frequently applied for system failure assessment in the aeronautical industry. On the other hand, the availability of any additional tool or method that contributes to the development of those activities is certainly very beneficial for the process.

3.1 Bond Graph-Oriented Method

From a failure assessment's standpoint, not all effects or parameters used to compose the system model are subject to relevant variations in their characteristics during the system operation. Related to physical properties, geometrical ones or constructive aspects, some elements present null or negligible variation in their properties throughout the useful life of the system. Hence the analyst challenge comprises the identification, among the main elements that constitute the system model, that is, energy stores, dissipators, sources, transformers, gyrators and control signals, of those more susceptible to variations arising from a fault occurrence.

Consequently, the visual discretization of the relevant effects allowed by the bond graph modeling and the energy concept behind it represents an advantage of its use to support failure analyses of aircraft systems. Depending on the details attributed to the effects of a particular component, reasoning about its failure modes from the elements that are part of the model seems to become an easy task. As a result, a preliminary evaluation of the susceptibility of each effect in the bond graph diagram to the occurrence of a fault can be accomplished in a straightforward and quick manner.

In order to illustrate the use of such facility, some effects of the bond graph models shown in Figure 9 to Figure 11 had been highlighted by means of a circle to denote those effects with the potentiality of presenting a discrepancy during the system operation, caused by a component malfunction or even by an incorrect maintenance procedure. Although it could have been made to other similar effects in the same diagram, like the several R elements of the valve manifold model, only dedicated ones were selected to illustrate the concept. The outcome of the aforementioned analysis is given by the relationship between each effect, its main characteristics and the potential faults, as summarized in Table 1.

Tab. 1. Fault analysis summary.

Effect	Main Characteristics	Potential Faults
Se_{press}	Aircraft hydraulic generation system	Generation system failure modes
Se_{return}	Representation of aircraft hydraulic system reservoir	Component inherent failure modes
C_{acc_1}	Nitrogen pre-charge value, fluid bulk modulus, internal volume and piston area	External leakage, jammed piston, air in line and incorrect N_2 precharge value
R_{check_ext} R_{check_int}	Internal construction and dimensions, density and fluid viscosity	Failed open, internal leakage, internal mesh clogging and failed closed (obstruction)
R_{hose7}	Hose dimensions, fluid density, internal surface roughness and Reynolds number	External leakage
PD_LH	Original architecture: pedal, springs and mechanical connections	Loss of mechanical connection and pedal jamming
AS_LH	Electrical control signals and sensors measurements	Noise, open/short and drift
R_{A2P_A}	Internal construction and dimensions, density and fluid viscosity	External leakage and internal mesh clogging
R_{A1A_T} R_{DA_T}	Internal construction and dimensions, density and fluid viscosity	Internal leakage, spool dynamics change and internal mesh clogging
R_{pilot_1}	Internal construction and dimensions, density and fluid viscosity	Internal mesh clogging
C_{pilot_1}	Pilot chamber volume and fluid bulk modulus	Air in line and external leakage
R_{spool}	Spool friction (O'rings)	Friction change

3.2 Selected Failures for Analysis

The simulation in LMS Amesim® model of particular failures in the hydraulic brake system under analysis is already provided in [14].

The following two simulations focus on the representation of some of the faulty conditions of Table 1 in both bond graph diagram and physical model, to demonstrate how the bond graph support can help enhance the physical understanding of the engineer about the system faults and their consequences.

The first faulty condition chosen for analysis comprises the incorrect nitrogen precharge value in one of the brake system hydraulic accumulators, which could be originated by a gas leakage in this type of accumulator or by a wrong maintenance procedure during its servicing.

Since the hydraulic capacitance applied to model the accumulator effect in the bond graph schematics is strictly dependent on the gas precharge value, the accumulator faulty situation can be described on it by simply replacing the respective C element by an updated one with a magnitude representative of that condition. Due to the direct change of the element property, symbolized in Figure 12 by the substitute term $\bar{C}_{acc\_1}$, the present fault has a multiplicative character.

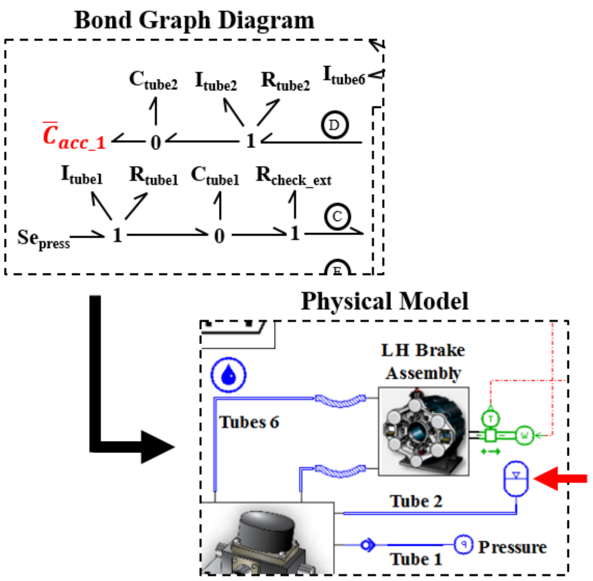

Fig. 12. Incorrect accumulator N_2 precharge.

As illustrated in Figure 12, the respective accumulator faulty condition can be easily implemented in the physical model of LMS Amesim® just by updating the gas precharge pressure parameter on the accumulator block with the new value. For the present simulation, a reduction of 60% of the nominal precharge value is assumed.

The second faulty condition selected herein is the internal leakage on the pilot control of antiskid valve 2nd stage. Figure 13 depicts the present valve manifold fault, which has an additive character since it can be described by the inclusion of an additional hydraulic resistance among the others that already exist in the component model. The respective resistance ($\bar{R}_{A2A\_A1A}$) is bonded to a 1-junction that denotes the pressure difference between the outputs of 1st and 2nd stages of antiskid valve.

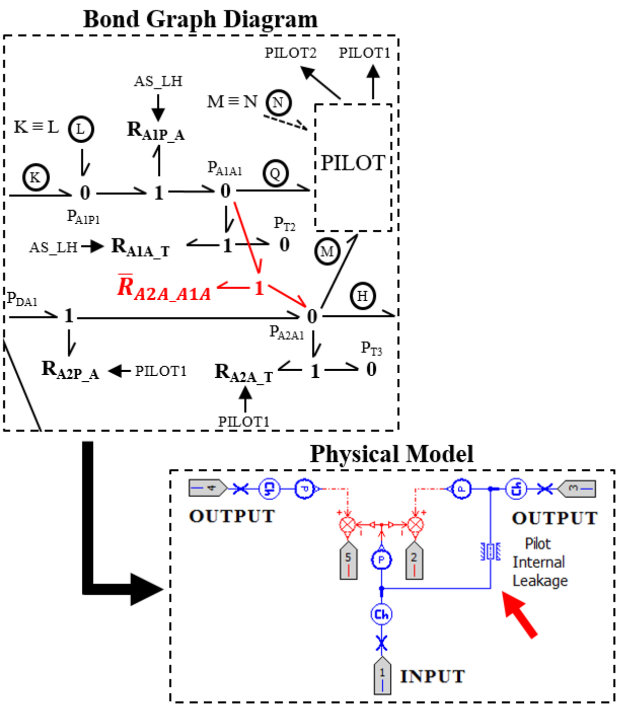

Fig. 13. Internal leakage in pilot control.

The representation of the pilot control faulty situation is done in Figure 13 internally to one of the pilot blocks, between the aforementioned pressure lines. Therefore, a fixed hydraulic orifice (laminar resistance) is positioned between them to simulate the internal leakage. Assuming that the fault is resultant of the degradation of one of the O'rings installed along the 2nd stage spool, the resistance can be characterized as a concentric-type orifice, with 0.1 mm of radial gap and 10.0 mm of length.

3.3 Simulation Results

The effects evaluation of the selected failure modes is deeply discussed in [13] for several brake system variables and also with respect to aircraft performance during a time slice of braked roll. The two graphs below aim to illustrate some of those impacts when the faulty conditions chosen in section 3.2 are independently implemented in the aircraft brake system.

Figure 14 describes the forward acceleration levels in aircraft center of gravity (C.G.) when the incorrect N_2 precharge value is simulated. As it could be later confirmed through a Fast Fourier Transform (FFT) analysis, the present fault is responsible for developing perceived additional vibrations in the aircraft, with relevant intensity in particular frequencies along its spectrum.

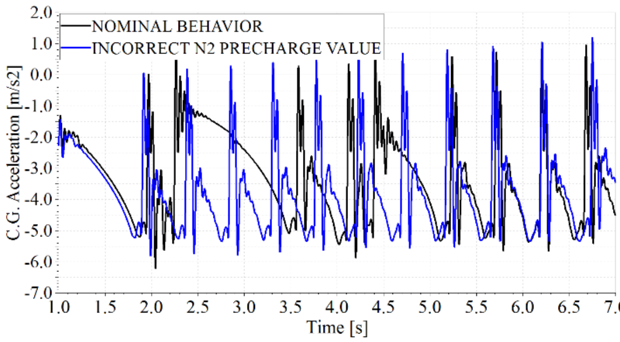

Fig. 14. C.G. acceleration: accumulator fault.

The brake pressure profiles in both pilot lines (normal and faulty) for the second failure condition are provided in Figure 15. The pressure behavior in the faulty line presents a high frequency oscillation close to the condition of completely released pressure, in the time interval of 1.0 to 2.5 seconds, which does not comprise a normal behavior of the system.

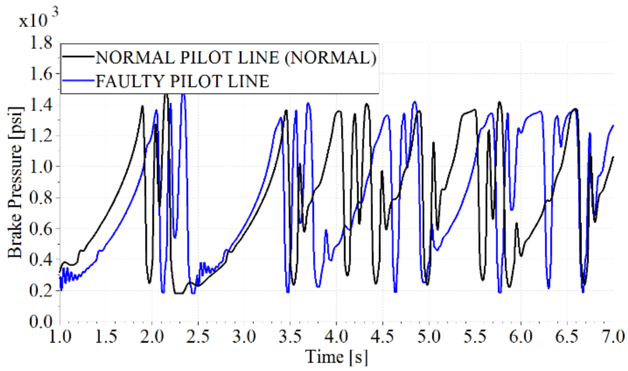

Fig. 15. Brake pressure: antiskid valve fault.

3.4 Definition of Post-Actions

A thorough analysis about the impacts of each failure mode shall be accomplished and required post-actions identified in order to keep the aircraft safe and economic operation.

The behavior described in Figure 14 might reveal a situation that can jeopardize the cabin comfort level. As a result, the development of a monitoring system for the accumulator precharge, the pursuit of a better reliability number for the accumulator gas leakage failure mode and a more frequent inspection of its servicing condition during maintenance are only some examples of post-actions which could be assessed as necessary for the respective failure.

Regarding the faulty condition in antiskid valve pilot control, a redesign of its sealing mechanism might illustrate an action that could be taken to minimize the failure effects or even to improve its failure rate.

4 Conclusions

The objective of the present work was to demonstrate the use of a failure assessment method that applies the physical modeling and the bond graph technique in a cohesive manner. An aircraft hydraulic brake system was used as the background for the simulations and analyses.

In a nutshell, the proposed method takes advantage of the available computational resources nowadays and the good comprehension allowed by the bond graph method.

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