STATEFLOW BASED HIBRID APPROACH TO VALIDATE AIRCRAFT ANTI-SKID BRAKING SYSTEM

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Abstract. *The purpose of this work is to use a hybrid approach based on Simulink / Stateflow tools to verify and validate against a set of engineering requirements the model of an anti-skid braking system for application in aircraft. Hybrid systems are dynamic systems that exhibit both, continuous and discrete event dynamic behavior. In this particular work, Statecharts in MATLAB's Statflow tool were used to model the discrete events. Anti-skid braking systems are systems that prevent tires from skidding during the landing run of an aircraft. The coefficient of friction between tires and runway is a function of the skid ratio, what is a relation between tires angular and linear speeds. Type of runway, runway contaminants, aircraft lift and weight do also play a significant role in braking performance. Modern brake control systems are capable of modulating the braking torque applied to the wheels, maximizing at all times the coefficient of friction regardless of the runway conditions. An additional function of the anti-skid braking system is the locked wheel protection, what prevents tires from deep-skidding and blowing. This validation task requires not only the brake control system to be modeled, but also the aircraft dynamics and the tires to runway interface. Tires to runway interface is an engineering problem that is itself challenging. It is known that the coefficient of friction drops abruptly at increasing braking torque, what characterizes the skid. This phenomena is more evident in wet or icy runways, and with low normal force on the wheels, like for instance in the beginning of the landing run where aircraft lift is still significant, or with the aircraft in a light weight configuration. Failure conditions and their effect in braking performance are also considered in the model. Typical failures in braking systems are associated, but not limited to pressure feedback, pressure transducers, pedal position transducers, servo-valves and wheel-speed transducers. The consequences of these failures are either the loss of the anti-skid function during the landing run, or the total loss of the braking function, forcing crew to make use of a backup emergency braking system.*

Keywords: *Hybrid Systems; Braking; Anti-skid; Verification and validation; Statechart*

1. INTRODUCTION

The purpose of this work is to use modeling and simulation techniques to validate the compliance to requirements by aircraft systems. This paper covers specifically the modeling and simulation of an aircraft anti-skid braking controller as a hybrid system, i.e. a dynamic system that exhibits both, continuous and discrete event dynamic behavior.

In continuous dynamic systems, the set of variables that model the system states change continuously through time. They are therefore described as time-driven. This feature is typical of systems that have their behavior determined by physical laws such as Ohm or Newton laws. Continuous dynamic systems are usually modeled by differential equations.

On the other hand, discrete event dynamic systems have state variables that are modified in a discrete way by the occurrence of instantaneous events. The time interval from the beginning to the end of an event is not relevant for the system dynamics when compared to the time intervals between events. Another important feature is the evolution of the state variables. They are constant between events and are modified in a discontinuous way by the occurrence of events. They therefore describe discrete event-driven states

A hybrid system has the benefit of encompassing a larger class of systems within its structure, allowing for more flexibility in modeling dynamic phenomena. Given the nature of the anti-skid system, with discrete states in the controller and a continuous dynamics in the wheels and brakes, the choice for hybrid modeling was natural.

There are many forms of state diagrams, which differ slightly and have different semantics. For this particular work the option for statecharts was made. A statecharts are extension of classical state machines. Their main advantage is the fact that they enable more simple specification and design of discrete event systems than other tools like for example Petri nets. Statecharts are modular and expressive, i.e. it is possible to describe complex behavior of the system with a relatively simple statechart.

This paper proposes a hybrid approach to the validation of anti-skid braking system requirements, using the modeling and simulation environment MATLAB™ / Simulink™ / Stateflow™. The choice for this environment was made as it enables the integration of continuous and discrete models into a single tool. Continuous dynamic systems were modeled in Simulink, while discrete states were modeled in Stateflow charts.

2. ANTI-SKID SYSTEMS

2.1. Basic Principles

The aircraft braking performance is dependent on the deceleration force that results from the friction between tires and runway. This deceleration force is the reaction to the braking torque. Deceleration force is given by Eq. (1), where μ is the coefficient of friction between tires and runway, N is the normal force acting on a tire (weight minus lift), τ_{br} is the braking torque and R_{rol} is the tire rolling radius.

$$F = \mu N = \frac{\tau_{br}}{R_{rol}} \tag{1}$$

Conventional braking systems are hydro-mechanical devices where hydraulic pistons compress a set of rotors and stators, generating friction between them, resulting in a braking torque. Braking pressure is a function of brake pedal displacement, being the system of the open loop type, without any information to the pilot about tire skid or locked wheels. Tire skid results in reduction of tire life or even tire failure, increased stopping distance and loss of control. This happens because the friction coefficient between tires and the runway is a function of the tire skid or slip ratio, as shown in the schematic μ-slip curve of Fig. (1). Skid ratio is given by Eq. (2), where ω is the wheel angular speed and V is the aircraft linear speed. Note that the coefficient of friction increases linearly with skid ratio for a certain range, but drops abruptly shortly after is maximum value, resulting in locked wheels and loss of control. This phenomena is more evident is contaminated, wet or icy runways.

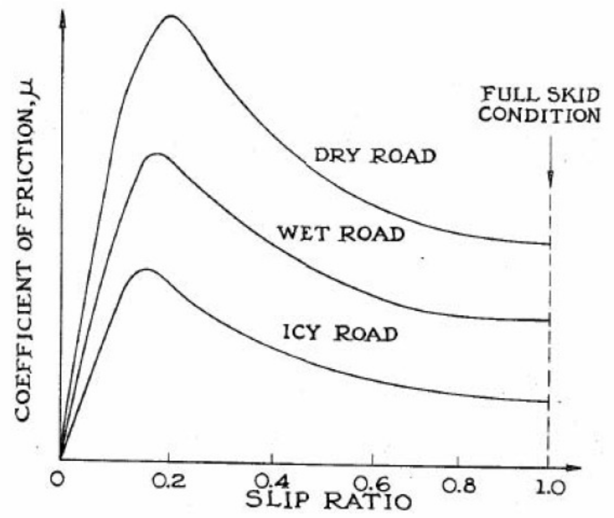

Figure 1. Coefficient of friction between tire and runway as a function of the skid ratio

$$SR = 1 - \frac{\omega R_{rol}}{V} \tag{2}$$

Anti-skid braking systems are of the closed loop type. Wheel speed feedback is compared to aircraft speed to identify tire skid and locked wheel conditions. The system controller acts on the brakes servo-valves releasing pressure in the intent to maximize the coefficient of friction and to prevent loss of control. A schematic braking system architecture is shown in Figure (2).

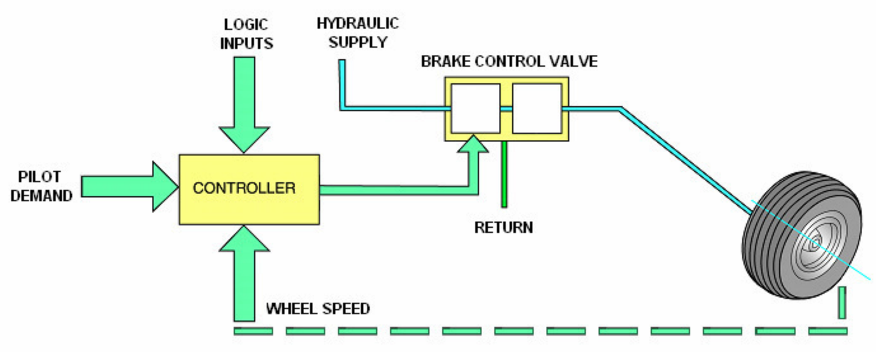

Figure 2. Schematic representation of an aircraft anti-skid braking system.

The SAE Committee A-5 (2006b) classifies anti-skid systems as ON-OFF, modulating and adaptive systems.

ON-OFF systems consist of three components: a skid and locked wheel detector, a control shield, and a solenoid valve. The detector is an electromechanical device, providing logic signals to the control shield. The control shield is a power conditioner containing a series of relays. The relays interpret logic signals from the detector and apply an electrical signal to the hydraulic solenoid valve, to dump or reapply metered brake pressure. This kind of system dates back from the late 1940`s and is still operating on the B-52 Bomber.

Modulating System, also known as Quasi-Modulating, generally rely on a wheel speed transducer which generates a signal proportional to wheel speed. Based on the input wheel speed information, the electronic control circuit determines if the wheel is going into a skid. A signal is supplied by the control circuit to an electro-hydraulic valve (the antiskid valve) which regulates brake pressure in a manner inversely proportional to control signal, releasing pressure when a skid is detected and reapplying it when the wheel recovers. But, unlike the ON-OFF system, the pressure is reapplied to a lower level and then ramped up until the wheel starts to go into a skid again. This eliminates the need for interaction by the pilot.

Adaptive Systems, also known as Fully Modulating, represent advanced control concepts which give optimized performance for both dry and wet runways. Usually high frequency wheel speed transducers are used which result in improved signal fidelity and response. Multiple data control functions, feedback of valve current, and nonlinear computing elements such as multipliers and dividers are combined to result in the adaptive control system. During the skid, corrective action on brake pressure is based on the sensed wheel speed signal. The major difference between the modulating and adaptive systems is found in the implementation of control in the electronic circuitry.

2.2 .Validation of Anti-skid systems

The validation of and anti-skid system implies in verifying its compatibility with the aircraft, tires, wheels and hydraulic power source.

Modeling and simulation has limitations over conventional aircraft level or dynamometer testing, as some effects may be difficult to model correctly or even overseen. The SAE Committee A-5 (2006a) gives directions to design and test aircraft anti-skid braking systems for total aircraft compatibility.

On the other hand, modeling and simulation is inexpensive when compared to testing and enables several different scenarios to be evaluated in a relatively short period of time. Test cases may be manually selected, or automatically generated as suggested by Moura (2004).

Another effective approach is to use HIL (Hardware-in-the-loop) simulation to integrate the real braking system controller with a dynamic model of the system hydraulic components, aircraft dynamics and runway interaction. Lee at al (2005) additionally considered the hydraulic system in conjunction with the dynamic model of tires, wheels and brakes. Mathworks (2003) describes the successful usage of HIL to solve an intermittent brake control issue in its Cessna aircraft.

A combination of all techniques is usually the most effective way to validate an aircraft system. The need to perform aircraft level tests is not being questioned, but extensive modeling and simulation may significantly reduce the number of test points. Some potentially dangerous test may also be replaced by simulation, as long as the model is validated and robust.

3. REQUIREMENTS TO BE VALIDATED

The requirements to be validated will be the braking efficiency and maximum skid ratio in dry, wet and combined runways, under full brakes application, as follows:

- Braking efficiency greater than 95% for dry runways;
- Braking efficiency greater than 80% for wet or combined runways;
- Skid ratio shall in no moment exceed 0,4.

The US Air force (1971) defines braking efficiency as the ratio between the minimum theoretical stopping distance and the actual stopping distance. This can be expressed as given in Eq. (3), where V_0 is the aircraft speed at brakes application, x is the aircraft stopping distance, μ_{max} is the maximum available coefficient of friction and g is the acceleration of gravity. An alternative method to determine braking efficiency is given by SAE Committee A-5 (2006b).

$$\eta = \frac{V_0 \, x}{2 \mu_{\max} \, g} \tag{3}$$

4. DESCRIPTION OF THE MODEL

The purpose of this work is the verification and validation of a hybrid anti-skid braking system, therefore a hybrid anti-skid braking controller was built. A model for the plant, including pilot input, aircraft dynamics, tires, brakes and tires to runway interaction was also built.

4.1. Plant

The plant built for this work is as shown in Fig. (3). The anti-skid controller imposes an electrical current to the brake servo-valve depending on pilot demand and also on wheel speed feedback. This current will result in a braking pressure and braking torque, creating a deceleration force that is function of the coefficient of friction between tires and runway. This deceleration force will finally determine the aircraft stopping performance.

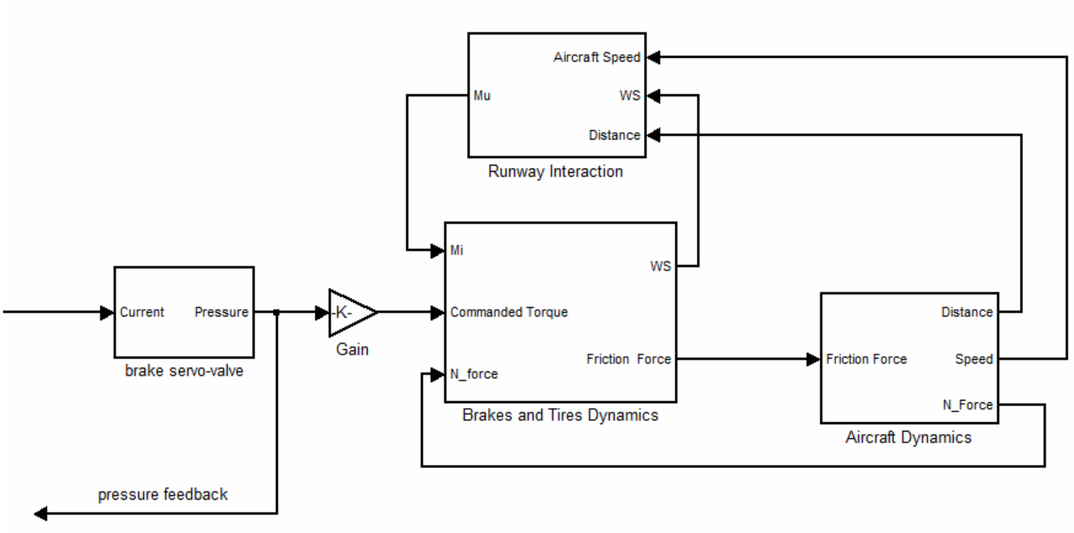

Figure 3. Plant including brake servo-valve, tires, runway and aircraft dynamics

The coefficient of friction between tires and runway result from its interaction according to μ-slip curves. μ-slip curves vary with aircraft speed, runway conditions and tire characteristics, and are therefore typically generated by tests. Generic μ-slip curves for dry and wet runways were included in the model, as well as a statechart containing information of the location of wet spots in the runway. The μ-slip curve for dry runways is exemplified in Fig. (4).

The model for the tires to runway interaction is shown in Fig. (5).

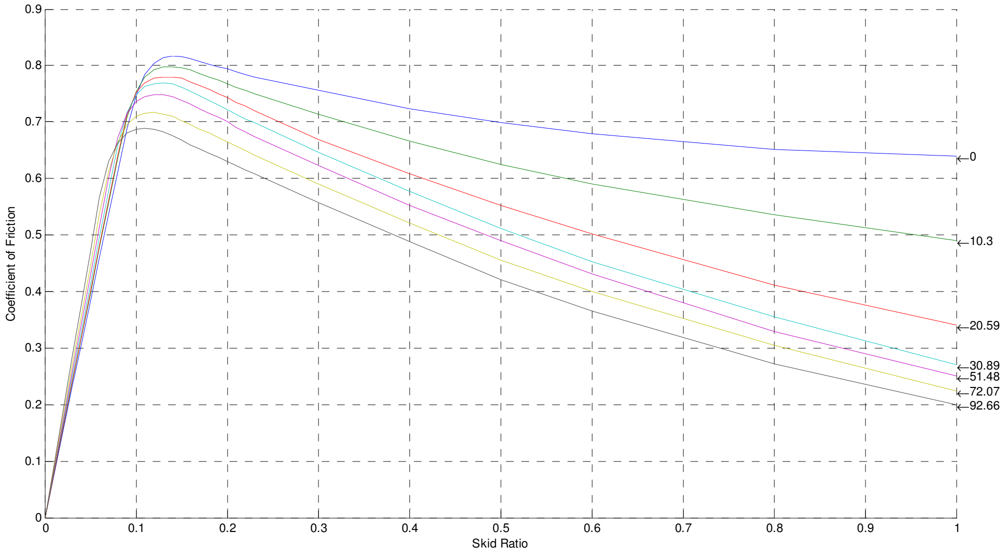

Figure 4. μ-slip curve for dry runway (speeds in m/sec)

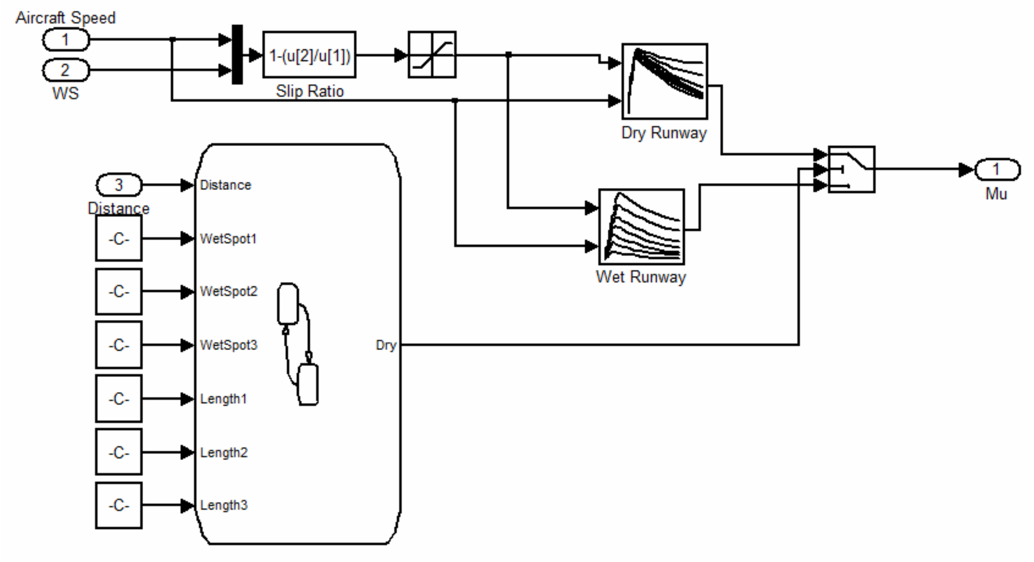

Figure 5. Model for the tires to runway interaction

4.2. Anti-skid Controller

The option for an Adaptive fully modulated system was made, similar to controllers in modern aircraft. The controller consists of continuous elements that provide electrical current to the brake servo-valves, and by discrete states modeled through a statecharts that enable the anti-skid and locked wheel protection functions. This statechart is shown in Fig. (6), and contains two states: DISABLED and ENABLED. The ENABLED state contains sub-states that trigger the anti-skid control and the locked wheel protection functions of the controller on and off. Whenever the anti-skid control function is enabled, a PID controller acts on the brakes servo-valve current to track a specific skid ratio. If the locked wheel state is triggered, brake pressure is released to speed the tires up and regain control.

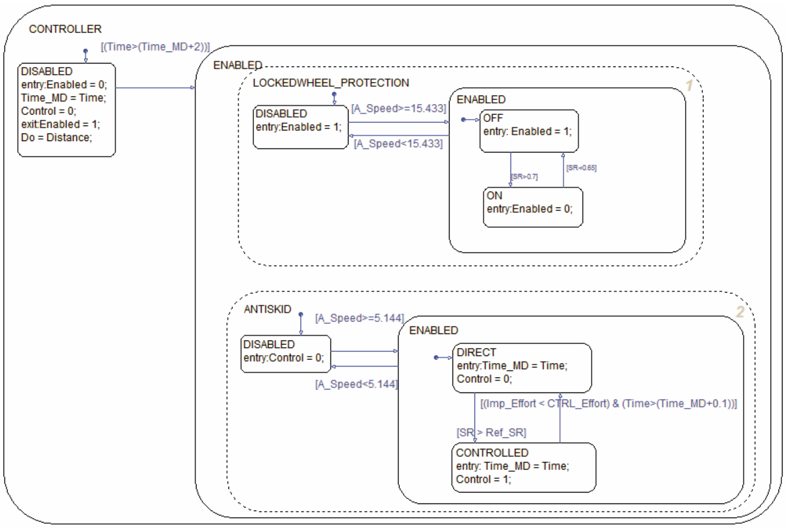

Figure 6. Statechart for the Anti-skid Controller

4.3. Fault Isolation

The controller monitors system parameters to identify and take actions upon previewed system failures. The states for the failure conditions are given in a dedicated statechart. Errors are introduced in the system as noise added to monitored parameters, like for instance the redundant pilot pedal command and pressure feedback versus commanded pressure.

The controller shall be able to compensate deviations up to a certain amount. If the pressure supplied to the brakes is for instance different than previewed due to deterioration in the braking servo-valve, the controller will adjust the electrical current and bring the pressure back to the desired level.

Certain declared mal-functions will trigger faults and fully disable the brakes. In real aircraft the crew would use the emergency brakes, which is an open loop system the supplies pressure to the brake pistons as a function of the displacement of the emergency brake lever. The emergency braking system is not scope of this work, and was therefore not modeled.

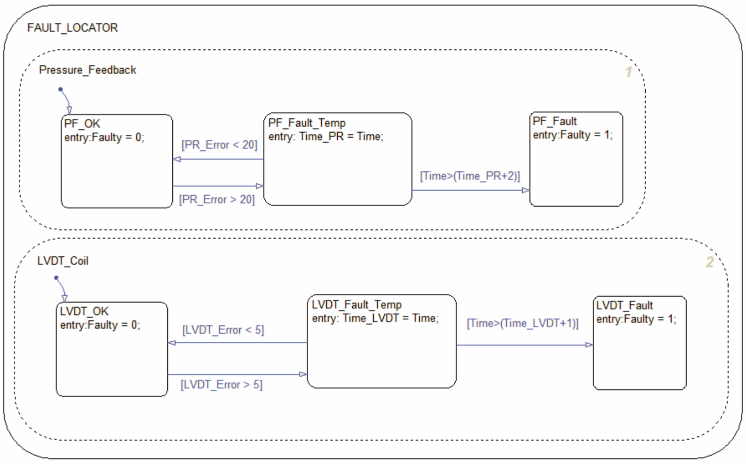

Figure 7. Statechart for the Fault Locator

5. TEST CASES

Three different test cases were built to verify and validate the performance of the anti-skid system:

- Maximum braking on a dry runway;
- Maximum braking on a wet runway;
- Maximum braking on a combined runway, with 3 wet spots, 20m long each, starting respectively 110, 180 and 230m after the runway touching point.

6. PRESENTATION OF RESULTS

A summary of the results is shown in Tab. (1). For all data presented, full brakes application starts 2 seconds after aircraft touchdown.

Table 1. Summary of results

Scenario	Stopping Distance	Efficiency	Maximum Skid Ratio
Dry runway	262 m	98,6%	0,112
Wet runway	469 m	92,3%	0,198
Combined dry/wet runway	306 m	92,9%	0,240

Simulation shows that the requirements are fulfilled, validating the proposed system architecture. The controller successfully managed to adjust brake pressure to maximize the coefficient of friction, even in a combined dry/wet runway with 3 wet spots. System behavior and aircraft response can be observed in Fig. (8) to Fig. (10).

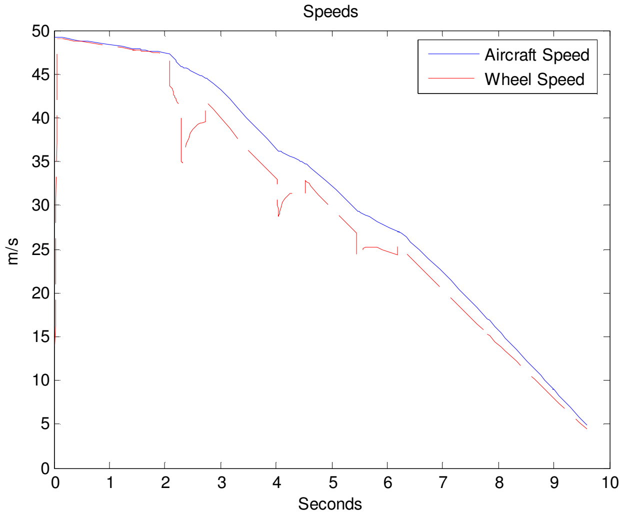

Figure 8. Aircraft and wheel linear speeds

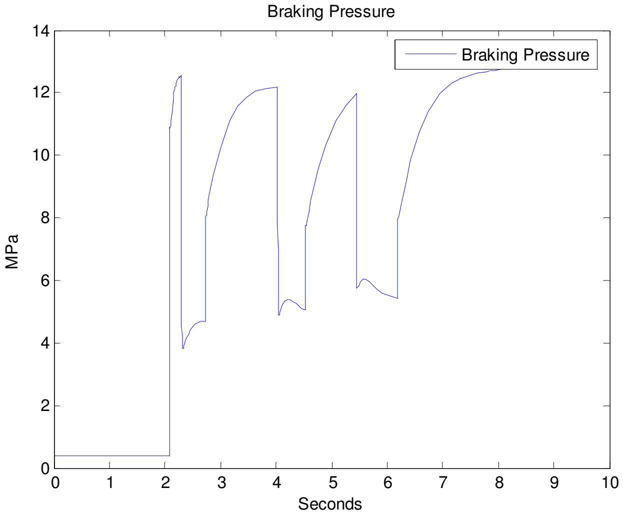

Figure 9. Braking pressure

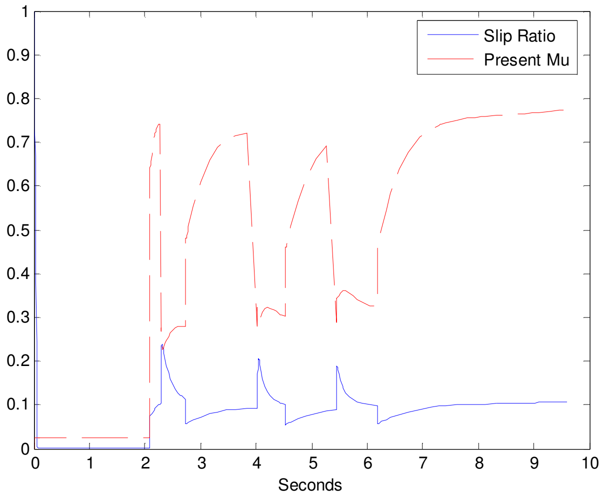

Figure 10. Slip ratio and coefficient of friction

7. CONCLUSION

This paper proposes a hybrid approach to verify and validate an aircraft anti-skid braking system. Despite not being validated against real aircraft braking data, the model presented consistent results showing that the anti-skid controller was successfully validated for the scenarios proposed. High braking efficiency was achieved for both, dry and wet runways, and skid ratio was also maintained at predicted values.

The interactions between the continuous and discrete parts of the model were well managed within the MATLAB® simulation environment, even though difficulty was initially observed to guarantee the integrity of the results in continuous-time modeling. Simulink's solver subdivides the simulation time span into major and minor time steps, where a minor time step represents a subdivision of the major time step. The solver uses results at the minor time steps to improve the accuracy, but results are only produced at major time steps.

Special care shall be taken to force states within the Stateflow charts to be maintained at minor time steps, and only to be updated at major time steps when mode changes occur. Using this heuristic, a Stateflow chart can always compute outputs based on a constant state for continuous-time.

8. REFERENCES

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