Development of Brake System with ABS Function for Aircraft

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Abstract: In this paper, it is to development of brake system with ABS function for aircraft. The test of brake system is required before applying on aircraft. The real-time dynamic simulator with 5-D.O.F. aircraft dynamic model is developed for braking performance test of ABS (Anti-skid Brake System) control h/w with anti-skid brake functions. The dynamic simulator is real-time interface system that is composed of dynamic simulation parts, master control parts, digital and analog in/out interface parts, and user interface parts. The 5-D.O.F. aircraft dynamic model is composed of a big contour and a little contour by simulation s/w. The big contour represents the interactions of forces in airframe, nose and main landing gear, and engines on the center of gravity. The little contour represents interactions of wheel, braking units, hydraulic units and a control unit. ABS control h/w unit with ABS control algorithm is also developed and is tested with simulator under the some conditions of gripping coefficient. We have known that ABS control h/w unit on wet or snowy runway as well as dry runway very well protects wheel skid.

Keywords: aircraft, aircraft dynamics, ABS, Anti-skid, Brake, real-time simulator, ABS controller, ABS algorithm, landing, wheel

1. Introduction

ABS (Anti-skid Brake System) has been applied to railways since the beginning of the 20th century. An application of ABS was extended to automobiles and aircrafts. The ABS for aircrafts is for increasing of landing security, shortening of landing distance as well as protecting against wheel skid. A general method of anti-skid control employs a digital control unit to detect a velocity of main landing wheel. The digital control unit decides a skid condition of the wheel and it protects the skid condition by controlling pressures of braking cylinders. In this paper, an ABS control algorithm is developed with a dynamic model of 6-D.O.F. (Degree of Freedom). The dynamic model is composed of a big contour and a little contour by MATLAB/SIMULINK. The big contour represents the interactions of forces on the center of gravity in airframe, nose and main landing gear and engines. The little contour represents interactions of wheel, braking units, hydraulic units and a control unit. The dynamic model is simulated by HILS (Hardware In the Loop Simulation) System. The digital control unit is constructed to accommodate the ABS control algorithm. The algorithm is verified by real-time closed loop test with HILS system and the test results are presented. The purpose of this test method is to develop a digital control unit with ABS control algorithm using HILS with real components. The digital control unit is tested under various road conditions. Test results on a dry runway (high friction) condition and on a wet or snowy runway (low friction) condition are presented. Applying the designed ABS control algorithm very well protects a wheel skid.

2. Real-Time HILS System

2.1 Real-Time HILS System

The Real-Time HILS System, which is shown in Fig. 1, is composed of fully realistic hydraulic brake system, real-time interface system and digital control unit with ABS algorithm. The real-time interface system is composed of a master board with DSP chip (60MHz), a Simulation board with ALPHA chip (600MHz), a wheel speed generation board and a multi-i/o board. Matlab/Simulink in the Host PC develops the dynamic model of aircraft with 6-D.O.F. and transfers it to simulation board. The simulation board simulates the dynamic model at real-time. During simulation, the real-time interface system generates speeds of left and right wheel to the digital control unit and inputs pressures of left and right brake from it. The hydraulic brake system is composed of real hydraulic valves, pipes, sensors and brake cylinders.

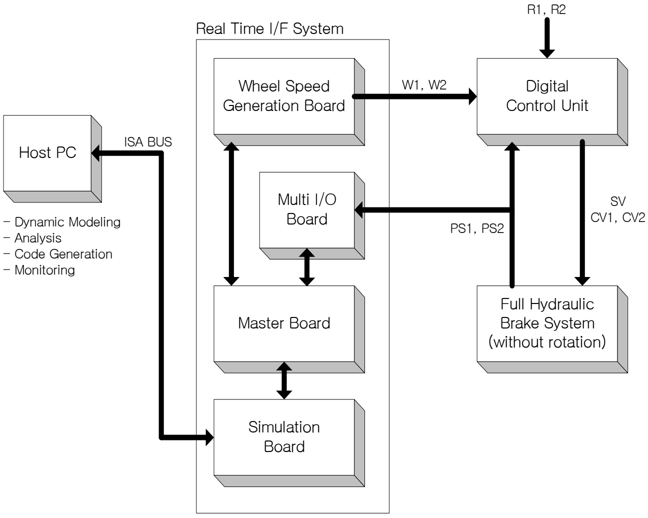

Fig. 1. Configuration of Real-Time HILS System.

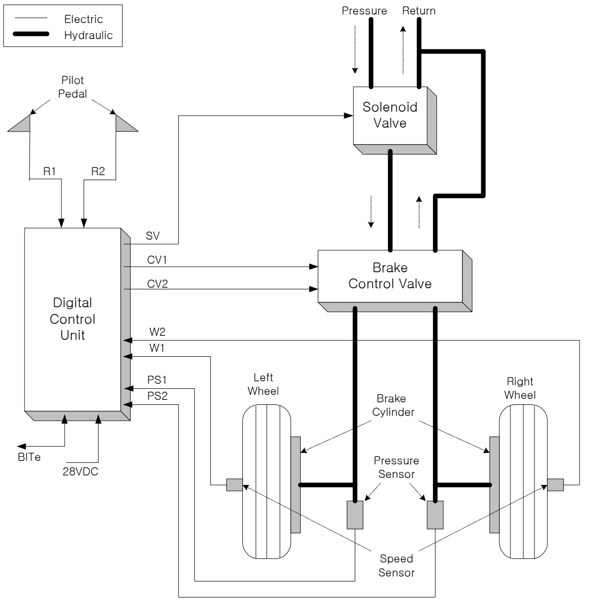

Fig. 2. Fully Hydraulic Brake System

2.2 Fully Hydraulic System

The hydraulic brake system for ABS, which is shown in Fig. 2, is composed of solenoid valve, brake control valve, brake cylinders, pressure sensors, speed sensors, pilot pedals, wheels and hydraulic pipes but wheels are not rotated because this brake system is installed on ground test bench instead of aircraft. Real-time interface system instead of speed sensors generates speed signals to the digital control unit.

2.3 Dynamic Model of Aircraft with 6-D.O.F.

The dynamic model of aircraft with 6-D.O.F., which is shown in Fig. 3, is composed of big contour and little contours of left and right.

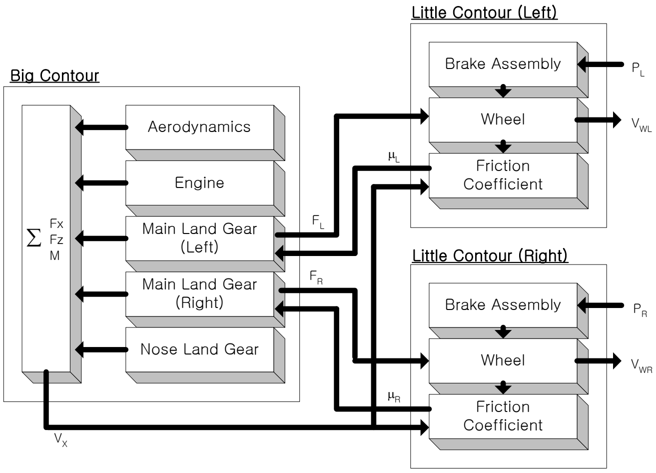

Fig. 3. Dynamic Model of Aircraft

The big contour of aircraft with 6-D.O.F., which is shown in Fig. 4, represents the interactions of forces that are composed of aerodynamics, engines, main landing gear of left and right and nose landing gear on the center of gravity of aircraft [1].

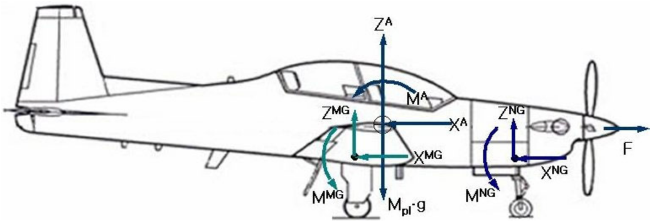

Fig. 4. Big Contour of Aircraft with 6-D.O.F.

The airframe is considered as a rigid body with mass localized in the center of gravity, it is loaded by the aircraft system of aerodynamic forces and moments (X^A, Z^A, M^A), total aircraft engine thrust forces and moments (X^E, Z^E, M^E), nose landing gear response forces and moments (X^{ng}, Z^{ng}, M^{ng}) and main landing gear response forces and moments (X^{mg}, Z^{mg}, M^{mg}). The dynamic model of big contour is described by the system of 6-order differential equations as follows [2]:

$$\frac{d^2x}{dt^2} = \frac{1}{m_{pl}}[X^A + X^E + X^{mg} + X^{ng}] \tag{1}$$

$$\frac{d^2z}{dt^2} = \frac{1}{m_{pl}}[Z^A + Z^E + Z^{mg} + Z^{ng}] - g \tag{2}$$

$$\frac{d^2\theta}{dt^2} = \frac{1}{J_{pl}}[M^A + M^E + M^{mg} + M^{ng}] \tag{3}$$

x, z – Horizontal and vertical coordinates of the airframe center of gravity in the earth coordinate system, m
θ – Pitch angle, rad
g – Free fall acceleration, m/s^2
m_{pl} – Airframe mass, kg
J_{pl} – Airframe main central moment of inertia relative to the lateral axis, Nms^2

The big contour generates aircraft speed (V_X) and vertical loads (F_L and F_R) of left and right landing gear to the little contour and inputs friction coefficients (μ_L and μ_R) of left and right between wheel and runway from it.

The little contour of left and right, is shown in Fig.3, represents interactions of brake assembly, wheel and friction coefficient. A reflection force on contacts between a wheel and a runway is shown in Fig.5.

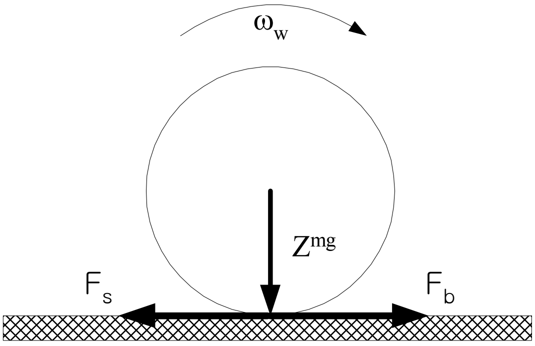

Fig. 5. Reflection Forces between Wheel and Runway

Here, The F_b is brake force and the F_s is friction force. This forces affects landing gear dynamic model in the big contour. The friction force of the wheel are described by equations:

$$F_s = \mu_s Z^{mg} \tag{4}$$

μ_s – Coefficient of the runway surface of the wheel (friction coefficient)
Z^{mg} – The wheel radial road, N

The friction coefficient is affected by slip(s) like Fig.6. The slip is described by equations:

$$s = 1 - \frac{\omega_w}{\omega_{fr}} \tag{5}$$

ω_w -Braking wheel angular velocity
ω_{fr} -Angular velocity of non-braking wheel

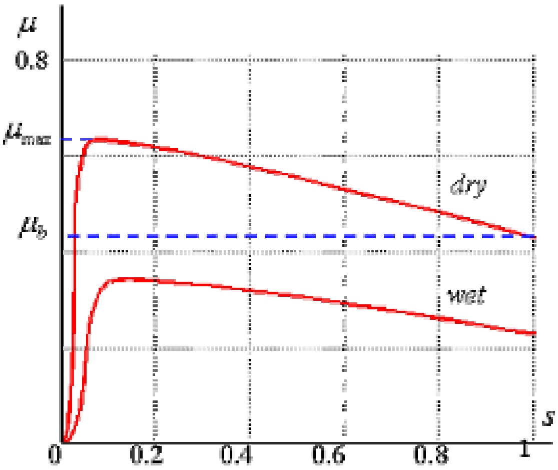

Fig. 6. Slip vs. Friction Coefficient

The brake model represents hysterics of brake static characteristic, dynamic loss at pressure feed and release. Fig. 7 shows hysteretic loop of brake characteristics.

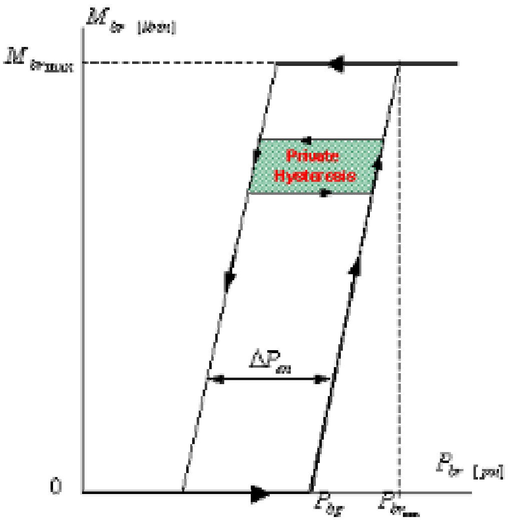

Fig. 7. Hysteretic Loop of Brake Characteristics

3. Digital Control Unit

3.1 ABS Control Algorithm

The control algorithm determines presentation of control unit's output signals depending on incoming signals and commands during operation of the unit in brake mode. Several situations (or Events) are defined to depend on conditions of incoming signals and commands in brake mode on runway. The ABS control h/w unit determines a situation and then generates a control signals. The situations for ABS control algorithm are shown in Table 1. The ABS control algorithm is composed of 10 situations. Situations of brake prohibition depending on aircraft conditions are 1E, 2E and 3E. Situations of braking operation depending on deceleration and slip ratio are 4E and 5E. These logics are occurred as Fig. 8. If the hysteric's band is not, some errors are occurred at transition point and then reliabilities are bad. Situation of pressure drop to initial pressure is 6E. Situation of slowing down pressure is 7E. Situation of finishing pressure drop is 8E. Situation of slowing up pressure is 9E. Situation of increasing pressure is 10E. An example of applying the situations is shown in Fig. 9.

Table 1. The situations for ABS control algorithm

Situations	Notes
1E	Blocking of pressure feeding until over speeding of the wheels
2E	Forbid of anti-skid working
3E	Forbid of working by deceleration
4E	Braking operation by deceleration
5E	Braking operation by skidding
6E	Pressure drop to return pressure
7E	Pressure correction
8E	Shelf endurance
9E	Searching pressure increase
10E	Pressure increase

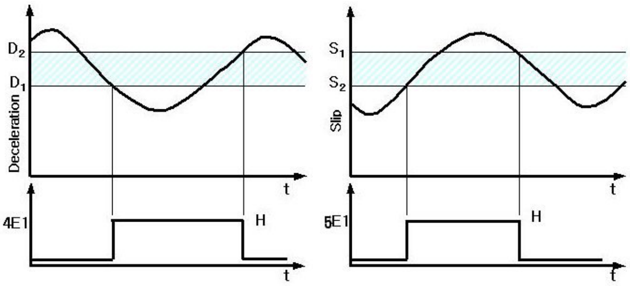

Fig. 8. Situation logics of 4E1 and 5E1

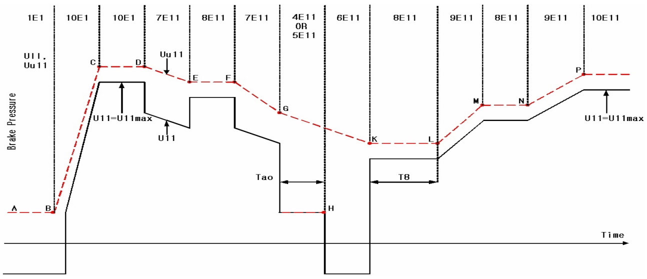

Fig. 9. Example of applying the situations

3.2 Digital Control H/W Unit

The ABS control algorithm is applied to ABS control h/w unit for anti-skid control. The main processor of ABS control h/w unit is TMS320C240-20MHz. The control unit has analog I/O to interface speed sensor, pressure sensor and etc as well as digital I/O to interface 28VDC-relays. The specifications of ABS control h/w unit are shown in Table 2.

Table 2. Specification of ABS control h/w unit

Items	Specifications
Main Processor	TMS320F240 – 20MHz
A/D	10 bit, 6.1 us, 6 ch.
D/A	8 bit, 7us, 5 ch.
PWM Output	10 KHz, 2 ch.
Speed Sensor Signal Input	400 – 5.2 KHz, sin wave, 2 ch.
Digital Input	28 VDC, 11 ch.
Digital Output	28 VDC, 5 ch.
Control Period	< 2 ms
Power Consumption	< 50 W

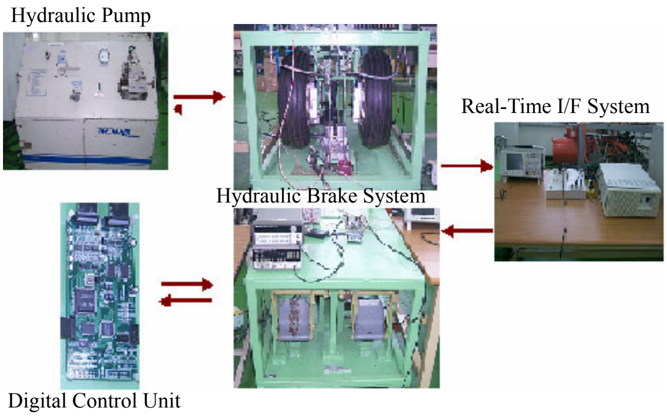

Fig. 8. Real-Time HILS System

4. Test and Results

The real-time HILS system is tested with digital control unit with ABS algorithm. The test system is shown in Fig. 9. The purpose of this test method is to develop an digital control unit using the aircraft dynamic model and an ABS control algorithm before on-board test in real aircraft. Several initial data is applied to test. The friction coefficient is important parameter among initial data. The developed system is tested to depend on some friction coefficients from dry runway ($\mu_{max}\cong0.62$) to wet or snowy runway ($\mu_{max}\cong0.3$). Test results are presented in Fig. 10, 11, 12 and Table III. The begin speed of the ABS function is 65 [knots] (≅120[km/h]) and the end speed of it is 10 [knots] (≅19[km/h]). Phenomenons of wheel lock (= wheel skid) are more occurred on wet or snowy runway than dry runway. The distance on dry runway is 296.6[m], it on wet or snowy runway is 379.4[m].

Table 3. Results after test with initial data

Initial Data	Braking Number			
	1	2	3	4
Object mass, lb	7300	7300	7300	7300
Brake pressure, psi	1400	1400	1400	1400
Max. Gripping	0.8	0.6	0.4	0.2
Braking Result	**Braking Number**			
	1	2	3	4
Stopping distance, m	476	487	502	562
Time of braking, s	19.0	19.5	20.7	24.1
Avg. deceleration, m/s^2	1.89	1.84	1.74	1.49

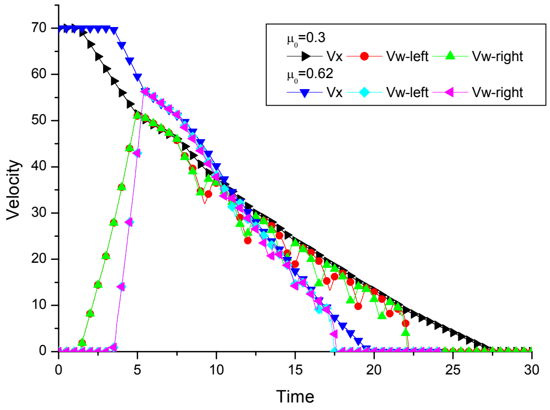

Fig. 9. Time vs. Speed

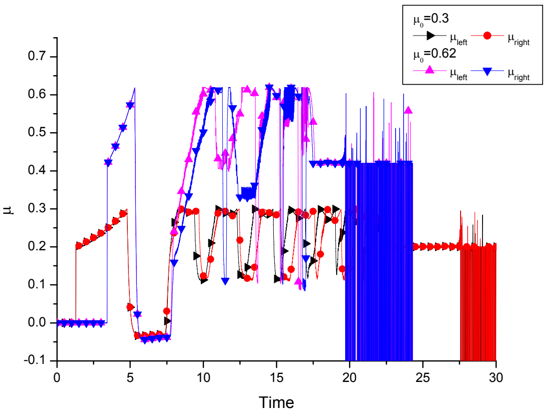

Fig. 10. Time vs. Friction Coefficient

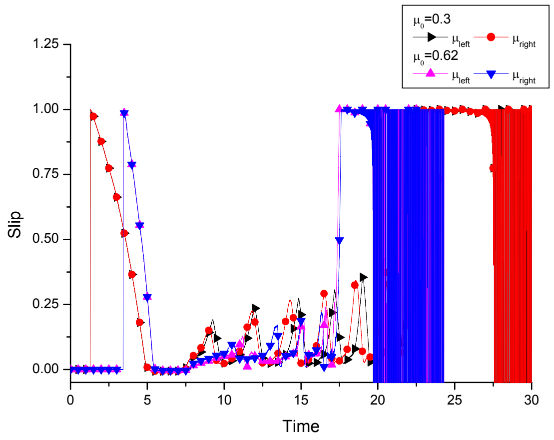

Fig. 11. Time vs. Slip

5. Conclusions

In this paper, the real-time HILS system with 6-D.O.F. aircraft dynamic model and digital control unit with ABS control algorithm are developed and are tested to depend on some conditions of friction coefficient parameter. The digital control unit very well protects wheel skid on wet or snowy runway as well as dry runway. Future works, the real-time dynamo system installed speed sensors will be tested with digital control unit

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