Evaluation of the Friction Coefficient from the Dynamometer Test of the Aircraft

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Abstract: In the braking system, the friction force is the most important factor of the design. For long time, many researchers have been strived for getting the exact friction coefficients. But the friction coefficients are affected by the road condition and changed by lots of parameters, such as normal force and characteristics between two contacted materials, temperature, etc. For the development of ABS of the aircraft, HILS(Hardware-In-the-Loop-Simulation) test and dynamometer test was carried out. For the calculation of the friction coefficients, the wheel moments were measured using the load cell mounted on the housing of the wheel. The test conditions were dry and greasy, as the 0.7 and 0.4 in friction coefficient, respectively. In this paper, the test results of the friction coefficients were represented and the improvement method was suggested.

Keywords: Anti-lock Brake System, Digital Control Unit, Dynamometer Test, Wheel Moment, Hydraulic Brake System

1. INTRODUCTION

ABS (Anti-skid Brake System) has been applied to many vehicles. And the application of ABS was expended to automobile and aircraft from railways. The aim of the ABS for the aircraft is assuring the braking security and shortening of the braking distance as well as the protection against wheel skid. The dynamic simulator was developed and finished the test using HILS. After HILS test, the brake performance and the effectiveness of the developed DCU were verified.

Before applying the developed ABS to real aircraft, the dynamometer test was proposed. An anti-skid control method used a digital control unit to detect a velocity of main landing wheel and then the digital control unit decided a skid condition of brake cylinders. During the test, the hydraulic pump was controlled by the signal commanded by DCU. Wheel velocity and dynamometer velocity are feedback to DCU that determines the brake pressure using the real-time interface system that is composed of master control parts, digital and analog in/out interface parts, user interface parts, and the signal fault confirmation graphic tool. The user interface part transfers test conditions from user to DCU and graphic test results from dynamometer to user. Before the dynamometer test, the ABS performance was confirmed from HILS test.

2. DYNAMIC MODELING

2.1 Dynamics of the dynamometer

For the dynamometer test, dynamics of dynamometer and wheel were modeled. The following figure describes the dynamometer, wheel and tire.

Dynamometer is a rigid disk rotating with heavy weight. Its mass and moment of inertia are equivalent to those of target aircraft. After this dynamometer rotates with initial speed and then starts to decelerate by the brake force and the friction force between two contacted surfaces. Next equation represents the motion equation of dynamometer for HILS test.

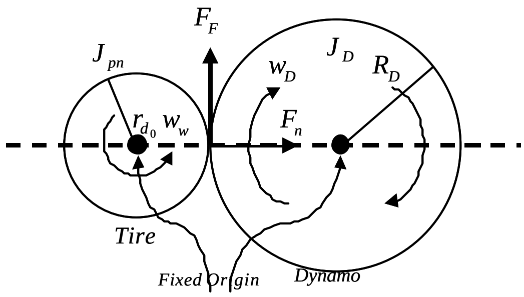

Fig. 1 Tire and Dynamometer model

$$\frac{d(w_D)}{dt} = \frac{1}{J_D}\left(-mF_n R_D\right) \qquad (1)$$

Here, w_D and w_w are the angular velocity of dynamometer and wheel, J_D is the moment of inertia of dynamometer. R_D is the radius of dynamometer.

To test the brake system performance, the operator pushes the wheel-tire system to dynamometer. That time, the dynamometer rotates with aircraft landing velocity. The tire moves and sticks entirely in dynamometer with constant force. The normal force F_n causes the friction force F_r that prevents the rotation of dynamometer then makes stop. Throughout these procedures, dynamometer imitates the real aircraft landing process.

2.2 Dynamics of wheel and tire

If the brake moment applies to the wheel then the wheel speed decreases. It causes the spring force and damping force between wheel rim and pneumatic tire. The wheel moment equation can be obtained applying those force to the moment equation.

In wheel moment equation, the deflection between rim and tire was considered. Wheel moment equation consists the wheel angular acceleration ($\dot{w}_w$) term acting on rim and the deflection (j_w) and its derivative (j_w) term between the wheel and tire. Fig.2 describes the simplified model.

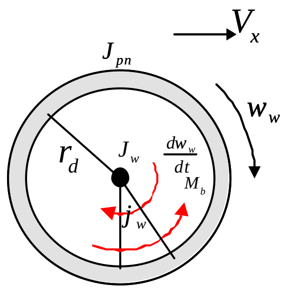

Fig. 2 Wheel and tire model

Here, J_w and J_{pn} are the moment of inertia of wheel and pneumatic tire, respectively. r_{d_0} is the initial radius of tire, V_x means the aircraft speed, and M_b is the braking moment acting on the wheel rim.

The final equation of the wheel angular acceleration can be written with three moment terms as following equation.

$$J_w \frac{dw_w}{dt} = -M_b + K_{wt}\frac{dj_w}{dt} + C_{wt} j_w \tag{2}$$

The left-hand side means the angular moment of inertia. In right-hand side, the first term is the braking moment acting opposite direction to the wheel rotation, the second term is the damping moment of tire, and the third term describes the spring moment. Those K_{wt} and C_{wt} are the damping coefficient of tire and the spring coefficient, respectively.

In next step, the deflection derivative equation is calculated. To get the equation of deflection, the total effects acting between rim and tire were considered with two parts; inner moments occurred by contacting with rim and outer moments occurred by tire friction. The following equation includes those effects totally.

$$\frac{d^2 j_w}{dt^2} = -\frac{J_w + J_{pn}}{J_w J_{pn}}\left[C_{wt} j_w + K_{wt}\frac{dj_w}{dt}\right] + \frac{1}{J_{pn}}\left[F_n + F_d\right] r_d \left[m_s - j_w\right] + \frac{1}{J_w} M_b \tag{3}$$

Here, m_s is the friction coefficient of tire. F_n and F_d is normal and damping force acting on the tire, respectively.

This equation composed of four parts. The first terms with bracket is the moments between rim and tire occurred by the spring force and damping force since the tire is pneumatic. These moment terms are considered in wheel angular acceleration equation. Here, the magnitudes are same but directions are opposite compared to those of wheel. The braking moment term is also. Next terms with the bracket are the moment caused by the friction force and the moment occurred by the rolling of the tire. From the equation (3), the normal force and damping force terms are determined to following equations. The normal force is considered same as the main gear absorber force. In the dynamometer test, this was set to constant force as 165,000N. The damping force is defined as the change rate of normal force.

$$F_d = K_{wn}\frac{d_{pn}(t) - d_{pn}(t-h)}{h} \tag{4}$$

$$d_{pn}(t) = \frac{F_n(t)}{K_n} \tag{5}$$

Here, d_{pn} is the deflection of the pneumatic tire by the normal force, K_{wn} and K_n means the radial damping coefficient and the radial stiffness of the tire.

The following fig.3 shows the load deflection of the pneumatic tire test that inner pressure was 140[psi]. With this deflection characteristic, the tire radius changes and then influences the braking force.

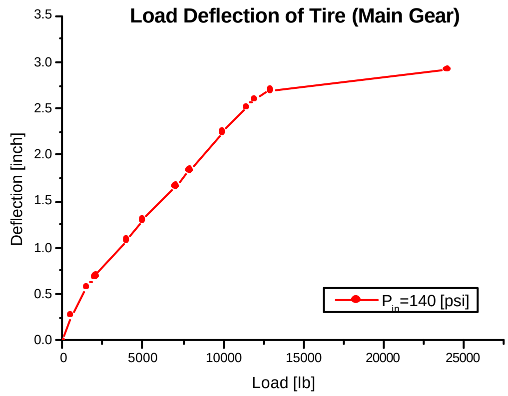

Fig. 3 Load deflection of the tire (140 [psi])

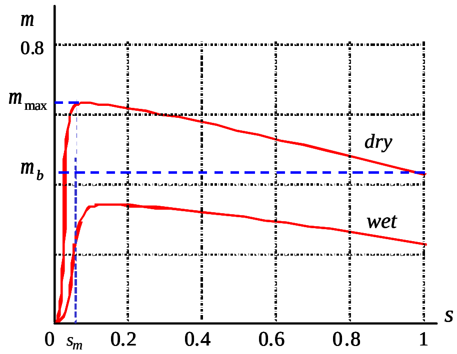

Fig. 4 Friction coefficient curve

2.3 Friction coefficient model

The friction coefficient varies with the road condition and the slip ratio. Generally, this characteristic curve is known as fig.4 with each dry, wet, and ice road condition. Seen from the figure, the friction coefficients can be divided two parts; increasing from zero to the maximum friction coefficient (m_{max}) at reference slip ratio (s_m) and decreasing from maximum value to m_b where slip ratio is equal to zero. So the friction coefficient can be defined as the function of m_m, s_m, and m_b.

$$m_s(s) = m_s(m_m, s_m, m_b) \tag{6}$$

Really, however, to know or to measure the exact value of friction coefficient is very hard and difficult. To get these friction coefficients, dynamometer test was carried out in this paper. The characteristic of friction coefficient will be shown and described in Chap. 4.

To maximize the braking efficiency, the system must be controlled that the slip ratio stays at the range around the maximum friction coefficient value. The slip ratio is defined as following equation.

$$s = 1 - \frac{w_w}{w_f} \qquad (7)$$

Here, w_w means the braking wheel angular velocity and w_f represents the free-wheel angular velocity. Free-wheel angular velocity is the reference velocity estimated from the measurements of the wheel and dynamometer velocity sensors. From the measurements, the reference velocity was equal to the dynamometer and it can be considered as the aircraft velocity.

2.4 Control moment model

As the actual hydraulic system is very complicated including non-linearity, it needs to be simplified and shows the hysteretic characteristics as the following figure. Because it has the different control moment at increasing and decreasing pressure condition, the dead-band was adjusted 20[atm] and the slope of the pressure-moment function was set as 924/1000[Nm/psi].

In this paper, using the hydraulic pump and digital control unit, the ABS and DCU performance test was carried out with the dynamometer and real aircraft wheel brake system.

Test results were described in chap 4.

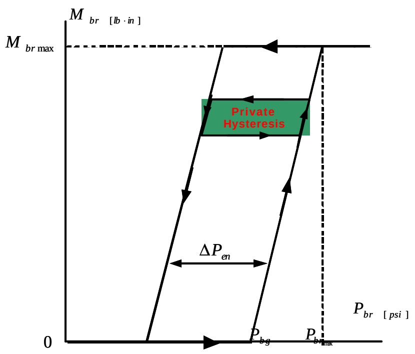

Fig. 5 Pressure hysteretic characteristics curve

3. DYNAMO TEST ASSEMBLY & CONTROL SYSTEM

3.1 Dynamo test assembly

The ABS test bed was assembled as the following figure. The interface system was received signals from DCU, the control unit, hydraulic system, and dynamometer. Then it sent the accepted signals to real-time interface system. For monitoring of the signals and control logic, BITe(Built-In-Test) and real-time monitoring system were developed. For the hardware control, the hydraulic pump and dynamo control system were handled carefully.

First, the dynamo velocity reached to the initial speed, the test wheel and tire pushed to the rotating dynamo by the external equipment. After the tire contacted to the dynamo, the brake system starts its operation to stop the dynamo system by the developed control logic. Repeating this process, the friction coefficients of several cases were calculated.

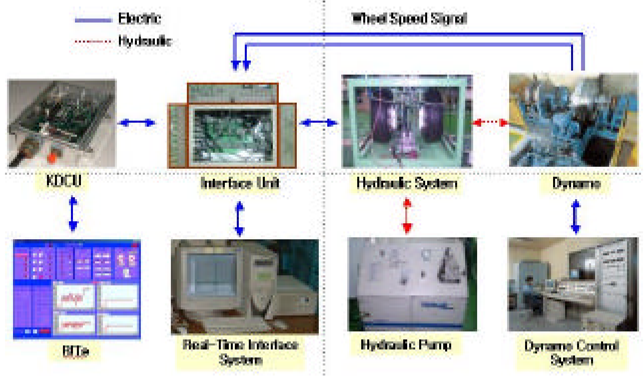

Fig. 6 Dynamo test assembly

3.2 Friction coefficient measurement

To evaluate the friction coefficients, the wheel speeds, normal forces, and braking moments were measured. From the load cell mounted on the housing, the net moment acting on the wheel could be measured. Then the actual friction force and the friction coefficient were calculated. From the eqn. (2) & (3), the moment equations can be simplified as next one.

$$M_{net} = M_{br} + M_{fr} + M_i \qquad (8)$$

$$m_s = \frac{M_{fr}}{r_d \times F_n} \qquad (9)$$

Here, M_{net} represents the net moment measured by the load cell stuck on housing, M_b the braking moment, M_{fr} the friction moment, and M_i the inertia moment. r_d is the radius of tire. Using above equations, friction force was calculated and then, finally, the friction moments was obtained.

The following figures show the dynamometer test assembly. To measure the wheel speed, speed sensors were attached both wheel and dynamometer. Fig.7 is the conceptual design at wheel side and fig.8 is that at the dynamometer.

Most of all, to get the friction coefficient, the most important factor of this test, load-cell attachment was conceptually designed as fig. 9. The load-cell was linked to the housing of the brake system. The ABS started to act, the housing was affected by the rotating moment and then this moment could be measured by load-cell along the linking arm.

Using the above method, more than 30 times of tests were performed. To imitate the low friction coefficient condition, the grease was coated on the surface of the tire and then the glassy case executed.

In the next chapter, the test results will be represented.

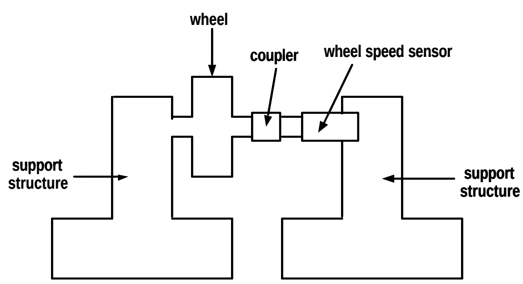

Fig. 7 Speed sensor attatchment conceptual design

(Wheel)

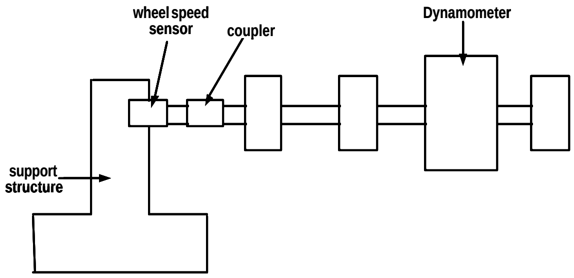

Fig. 8 Speed sensor attachment conceptual design (Dynamometer)

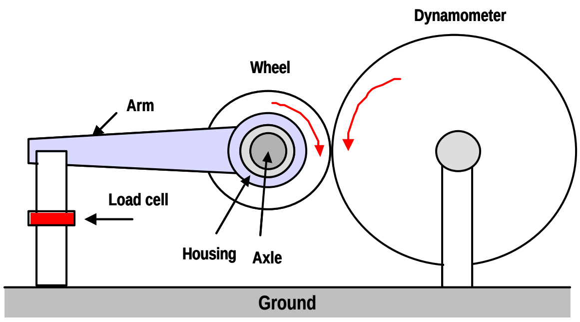

Fig. 9 Load-cell attatchment conceptual design

4. TEST RESULTS USING DYNAMOMETER

Dry and greasy surface conditions were tested. At dry condition, the friction coefficient was distributed from 0.5 to 0.75. The greasy condition was from 0.3 to 0.45. Generally, at dry road condition, the locking phenomenon doesn't occur and also could be observed during the test. Contrast, at the glassy condition, to prevent the wheel locking, the ABS operated frequently, so that the friction coefficient curve was different from that of the dry condition. Fig. 10 and 11 shows the test results at dry condition and Fig. 12 and 13 do at greasy condition.

Originally, ABS was designed to control the wheel velocity with constraint of slip ratio, not exceed 0.2. Seen from the fig. 10 and 13, slip vs. friction coefficient curves show that this test results satisfy the design condition.

To imitate the low friction coefficient condition, grease oil was coated on the surface of the tire. Because of grease, there was occurred an expected appearance. The test result at May 20 shows such case. This occurrence was happened at dry condition by that grease. These phenomena were repeated at low friction condition. The grease was put together continuously until it excesses slip limitation. At low friction condition, this took place frequently.

5. CONCLUSION

The dynamo tests were executed to calculate the friction coefficient, one of the most important parameters for braking system but unknown. The dry and glassy under grease condition was tested and then the resultant coefficients could be gotten similar to the expect values which got from the reference [4]. At dry condition, the friction coefficients were distributed from 0.5 to 0.75, and at the glassy condition did from 0.3 to 0.45.

Through the dynamo test, the ABS performance with same mass and inertia of the aircraft also was verified.

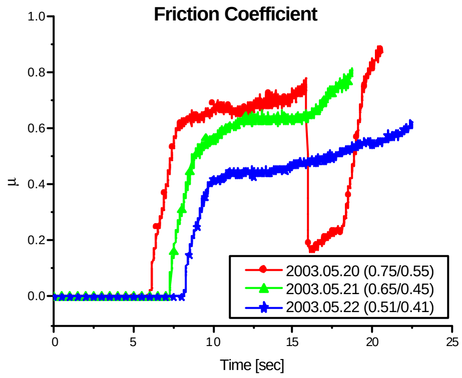

Fig. 10 Friction Coefficient Variation (high mu)

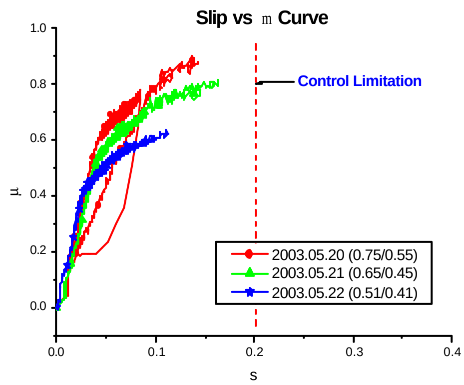

Fig. 11 Slip vs mu Curve (high mu)

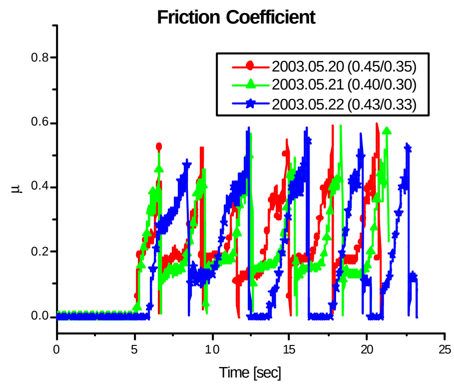

Fig. 12 Friction Coefficient Variation (low mu)

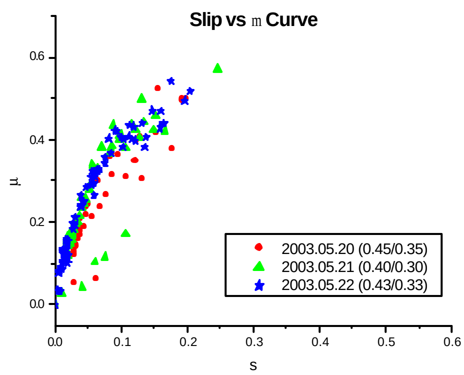

Fig. 13 Slip vs mu Curve (low mu)

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