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Skid Control Performance

CANCELLATION NOTICE

This document has been declared "CANCELLED" as of February 2002 and has been superseded by ARP1070B. By this action, this document will remain listed in the Numerical Section of the Aerospace Standards Index noting that it is superseded by ARP1070B.

1. SCOPE:

This Aerospace Recommended Practice (ARP) provides recommended methods for measuring performance of skid control systems. It includes test items and equipment.

1.1 Purpose:

The purpose of this ARP is to recommend, for design and evaluation purposes, methods of defining skid control system performance criteria.

2. APPLICABLE DOCUMENTS:

2.1 Military Publications:

Available from Standardization Documents Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

2.1.1 MIL-W-5013K: Military Specification Wheel and Brake Assemblies, Aircraft General Specifications for October 29, 1982.

2.1.2 MIL-B-8075D: Brake Control Systems, Antiskid, Aircraft Wheels, General Specifications for February 24, 1971.

2.2 Other Documents:

2.2.1 Stubbs, Sandy M.; Tanner, John A.; and Smith, Eunice G.: Behavior of Aircraft Antiskid Braking Systems on Dry and Wet Runway Surfaces. A Slip-Velocity-Controlled, Pressure-Bias-Modulated System NASA TP 1051, December 1979.

2.3 Definitions:

The performance of the skid control system has two aspects which must be considered: System stability and system stopping performance.

2.3.1 SYSTEM STABILITY: System stability requires that no unwanted oscillations occur within the system. The primary source of stability problems in the skid control system has been the excitation of the fore-and-aft mode of the landing gear strut, commonly referred to as "gear walk". Instability can also occur within the control loop of the system itself.

2.3.2 SYSTEM STOPPING PERFORMANCE: System stopping performance pertains to determining how close the skid control system comes to providing optimum braking while maintaining adequate cornering capability. In the broadest sense, system stopping performance includes the braking capability of the entire aircraft, and can be judged on the basis of stopping distance or related parameters, airplane deceleration, average braking force or average friction coefficient (μ). In the narrower context, only the skid control system's capability is evaluated.

3. DISCUSSION:

Skid control performance is being specified in greater detail in procurement specifications. Standard procedures are necessary to test and evaluate equipment. The following paragraphs will describe various test methods and recommended procedures for evaluation of system performance.

4. TESTING:

Because it is neither the purpose nor scope of this document to modify existing FAA or military documents, the following paragraphs are test recommendations only.

Five types of tests can be performed on skid control systems:

a. Airplane
b. Simulator
c. Dynamometer
d. NASA Langley Research Center Aircraft Landing Dynamics Facility (ALDF)
e. Other Track Test Facilities

4.1 Aircraft Testing:

Airplane tests are the final proof that the braking system meets its performance requirements. This applies both to stability and stopping performance.

4.1.1 Data: During aircraft tests, information regarding the following should be noted:

a. Aircraft configuration including weight, center of gravity, throttle settings, spoiler position, and flap position

b. Approach/touchdown speed

c. Runway location, condition, type, and slope

d. Tire and brake - types and wear conditions, tire inflation pressure

e. Atmospheric conditions - wind speed and direction, temperature, atmospheric pressure

f. Detailed system configuration

The aircraft should be instrumented to measure and record the following:

a. Wheel speeds
b. Airplane ground speed
c. Airplane longitudinal deceleration
d. Airplane pitch angle
e. Engine throttle positions
f. Spoiler handle position
g. Strut compressions (nose and mains)
h. Brake torques
i. Brake pedal positions
j. Metered hydraulic pressure
k. Pressure at brake inlet ports
l. Pressure in return lines
m. Center stator temperature on each brake
n. Antiskid control valve signals
o. Landing gear vertical loads
p. Landing gear side loads
q. Landing gear drag loads

4.1.2 Test Conditions: The following test conditions should be run for the specific systems.

4.1.2.1 Replacement Systems: Where standard certification data on an aircraft equipped with a skid control system are available, select six or more of those performance critical stop conditions in which the antiskid system was active, the aircraft was equipped with new tires, and the condition of the brakes was documented. Repeat those stops with the replacement antiskid system and compare the stopping distance with that from the original certification, or, if available, compare performance using an appropriate version of Method 1 from 5.1.

4.1.2.2 New System on a Noncertified Aircraft: Run at least six stops with the aircraft weight in the range in which the antiskid system will be providing active control. Determine performance using an appropriate version of Method 1 from 5.1.

4.1.3 Assessment: Airplane testing is the preferred test method since it evaluates actual usage. However, flight testing can be very expensive.

4.2 Simulator Testing:

Simulator testing is an efficient method of evaluating antiskid system performance. The simulator provides the most cost-effective means of conducting a wide range of controlled tests on the antiskid system. In addition, use of the simulator permits access to variables and the ability to conduct parametric studies which allow an accurate assessment of the performance of the system. However, simulators should be matched to the airplane using the test data.

4.2.1 Equipment Required: The simulator used to evaluate the antiskid system performance must include the primary antiskid components under test, namely, the control electronics and the antiskid control valve. Simulation of these components would most likely result in overoptimistic performance estimates. Hence, the simulator should include a hydraulic mockup of the brake system including the components from the brake metering valve to the brake. The return line pressure, diameter, and length should also be matched. The main function of the hydraulic mockup is to duplicate the hydraulic response of the skid control system. The computer simulation should include airplane and landing gear dynamics, tire/runway friction force generation models, and brake torque generation models. The brake torque models should include the dynamic torque-pressure frequency response. Where possible, the results obtained from the simulator should be correlated with airplane flight test data.

4.2.2 Test Conditions: The antiskid system should be tested over the operational weight and speed range of the aircraft for ground operations.

Testing should be conducted with:

a. Consistent tire to runway friction levels from 0.05 to the maximum expected ground coefficient (usually about 0.60)

b. A wet runway profile (μ increasing as speed decreases)

c. Step changes in runway friction coefficient

4.2.3 Assessment: Computer simulation can be viewed as a static test technique since there are no rotating wheels, tires, or brake rotors included in the test equipment. This technique generally evaluates response times and hydraulic lags of the skid control device. The fidelity of this test technique can be improved by the inclusion of experimentally verified brake torque-pressure frequency response characteristics obtained over a range of operational conditions. These data should be available from the brake manufacturers who must generate these data during dynamometer testing to satisfy specification requirements.

4.3 Dynamometer Testing:

Dynamometer testing consists of stops using passive inertia (also known as inertia equivalent) or active control of the dynamometer road wheel dynamics to simulate the aircraft. Dynamometer testing provides the capability of performing stops with the complete antiskid system loop, including the control electronics, the antiskid control valve, the wheel speed transducer, and an active brake. To complete the simulation, either the landing gear strut or a strut simulator should be included in the test.

4.3.1 Equipment Required: The dynamometer test should include the following minimum equipment: a wheel, brake, and tire; a simulated axle; the wheel speed transducer; and a mockup of the brake hydraulic system including the brake metering valve, the antiskid control valve, and hydraulic tubing representative of that on the aircraft. Inclusion of a dynamic simulation of the landing gear fore-and-aft motion is necessary to assess gear dynamic response. For all tests performed, the following quantities should be recorded with respect to time:

a. Hydraulic pressure at the skid control valve inlet port
b. Hydraulic pressure at the brake inlet port
c. Dynamometer speed
d. Aircraft wheel speed
e. Skid control valve signal
f. Brake torque
g. Drag force (Ground Reaction Force) if available
h. Wheel load
i. Brake pedal transducer position (for brake-by-wire systems)

4.3.2 Procedure: The aircraft wheel radial load should be applied by a loading mechanism which controls the ram pressure to reflect the aircraft loads during braking.

Consideration should be given to adjusting the tire inflation pressure for appropriate deflection for each load condition.

4.3.2 (Continued):

Both lift and weight transfer effects (due to deceleration) should be taken into account. The weight transfer may be computed on the basis of aircraft landing gear geometry and center of gravity location alone. The weight transfer associated with nose gear flexibility/compression may be ignored.

System performance can be evaluated using the methods described in 5.1.1 and 5.1.5.

4.3.3 Assessment: From a performance standpoint, dynamometer testing has several shortcomings. Most dynamometers do not account for the deceleration component due to aerodynamic drag. This can affect the antiskid system control characteristics. The curvature of the road wheel distorts the contact region of the tire and the friction characteristics of the rubber on steel are different than those of rubber on concrete or asphalt. In addition, gear walk stability is not easily assessed and may not be conclusive on a dynamometer, even if an actual gear is used. Because of these factors, the correlation between the performance of a system on the dynamometer and the system on a runway is not identical.

However, dynamometer testing can be viewed as dynamic testing since rotating wheels, tires and brake rotors are included in the test equipment. The fidelity of these dynamometer tests can be improved by the inclusion of "pitch-plane" landing gear simulation fixtures that reduce road wheel curvature effects and duplicate the fore-aft dynamic response of the aircraft landing gear. The fidelity of these dynamometer tests can also be improved by using aerodynamic drag simulation and programmable tire load-speed profiles.

4.4 NASA Langley Aircraft Landing Dynamics Facility Testing:

The Aircraft Landing Dynamics Facility (ALDF) at NASA Langley Research Center has a unique capability to test the dynamic characteristics of a complete landing gear with wheels, brakes, and tires under a controlled set of test conditions. An actual landing gear can be loaded up to a maximum load of 70 000 lb in a large carriage and tested at speeds up to 220 knots. The runway test section is 1800 ft long and can be paved in concrete or asphalt, with or without pavement grooves. The pavement surface may be dry, wet, flooded, or covered with ice and snow.

This facility is ideal for testing total system compatibility of the landing gear and control loop stability in the absence of aircraft tests. In some situations, such as the Space Shuttle orbiter, this may be the only option available. The gear can be tested under a set of normal or adverse operational conditions.

4.4 (Continued):

Normally, assessment of antiskid performance (airplane stopping capability) is not recommended on ALDF because of the inability to duplicate such individual aircraft characteristics as aerodynamics, engine thrust, load transfer between the main and nose gear during braking, and aircraft deceleration profile. Furthermore, the facility is not long enough to evaluate a complete braking stop through the total speed range during a single test sequence. Lack of ALDF availability is another reason for not recommending testing there. Frequently, there is a long test program backlog on ALDF and this would cause a real problem for an airplane program which usually has a two-year design phase.

However, in the absence of airplane and/or simulator tests, ALDF can be used efficiently to test the total brake control system compatibility with the gear to ensure that no oscillatory vibrations are introduced. The gear can be tested (within the limits of vertical loading) at various brakes-on speeds to ensure system compatibility. An indication of the system assessment using ALDF is given in 5.4.

4.5 Other Track Testing:

Other test tracks are available including the Naval Air Test Facility (NATF), which may be configured for full gear installation testing. This facility has similar limitations to the NASA Langley ALDF, but for some aircraft applications, full-stop testing may be possible.

5. DETERMINATION OF ANTISKID SYSTEM PERFORMANCE:

5.1 Aircraft Tests:

Stopping distance performance for the airplane should be determined from measured stopping distance, and may be presented as an average friction coefficient or as an antiskid system efficiency. The average friction coefficient or antiskid system efficiency can be calculated by any of the following methods.

5.1.1 Method 1A: The average friction coefficient is calculated by first calculating an average braking force. This average braking force is obtained by recording the instantaneous values of the brake torque and wheel rotational velocity for each braked wheel during the stop. Brake energy is calculated by integrating the product of brake torque and wheel speed from brake application to stop.

$$BE = \int_{t_A}^{t_R} (TB \cdot \omega)\ dt \qquad \text{(Eq. 1)}$$

5.1.1 (Continued):

where:

- BE = Net brake energy from a single brake
- TB = Measured brake torque
- ω = Measured wheel angular velocity
- t_A = Time of brake application
- t_R = Time of brake release

The net brake energies from all the wheels are summed and the average braking force is obtained by dividing the total net brake energy by the measured stopping distance, while accounting for the energy absorbed by the tire (wheel bearing rolling resistance is assumed to be negligible).

$$BET = \sum_{i=1}^{NB} BE_i \qquad \text{(Eq. 2)}$$

$$FBA = \frac{BET}{SB} \cdot \frac{100}{PCEB} \qquad \text{(Eq. 3)}$$

where:

- FBA = Average braking force
- BET = Total net brake energy
- BE_i = Brake energy for brake i
- NB = Number of brakes
- SB = Measured stopping distance from brake application
- PCEB = Percent of total energy absorbed by brakes

The percent of total energy absorbed by the brakes, PCEB, in Equation 3 is included so that FBA can also include the energy absorbed by the tires. Reference 2.2.1 presents equations for estimating the braking energy dissipated by the tire during aircraft braking and cornering maneuvers as a function of the tire braking and/or cornering forces and the wheel slip ratio. Furthermore, Equation 3 is derived such that the energy absorbed by the brakes and tires is isolated from all the other braking forces associated with an aircraft stop that are not related to the brakes. Examples of these ancillary forces, which are identified in Reference 2.1.1, include aerodynamic drag and retardation forces from such sources as deceleration parachutes and reverse thrust.

The average friction coefficient is the average braking force divided by the aircraft weight minus the average aerodynamic lift minus the average load on the unbraked nose wheels.

$$\mu_A = \frac{FBA}{(WT - LIFT_A - F_{NA})} \qquad \text{(Eq. 4)}$$

5.1.1 (Continued):

where:

μ_A = Average friction coefficient
WT = Aircraft weight
$LIFT_A$ = Average aerodynamic lift
F_{NA} = Average load on unbraked nose wheels.

The expression in the denominator of Equation 4 represents the load on the main-gear wheels. The relationship between main-gear wheel loads, aircraft geometry, and braking drag is illustrated in Figure 1.

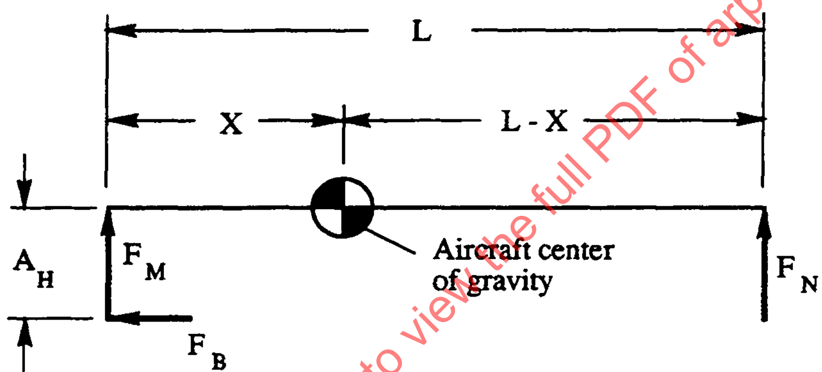

FIGURE 1 - Aircraft Landing Gear Geometry

$$F_M = \frac{F_N(L - X) - F_B A_H}{X} \quad \text{(Eq. 5)}$$

where:

L = Spacing between nose and main gears
L-X = Distance from center of gravity to nose gear
X = Distance from center of gravity to main gear
A_H = Axle height above ground contact
F_B = Braking force
F_M = Main-gear load
F_N = Nose-gear load

5.1.2 Method 1B: This method is identical to Method 1A except that the percent of total energy absorbed by the brakes variable, PCEB, is eliminated from Equation 3 which then becomes as follows in Equation 6:

$$FBA = \frac{BET}{SB} \quad \text{(Eq. 6)}$$

5.1.2 (Continued):

and FBA is the braking force due to the brakes only. Some manufacturers consider this method to be a better indication of antiskid performance than Method 1A.

5.1.3 Method 1C: In this method the average friction coefficient is calculated indirectly from the measured stopping distance. A value for the average friction coefficient is assumed and the stopping distance is calculated based on engine thrust and aerodynamic lift and drag. The calculated stopping distance is compared to the measured stopping distance and the friction coefficient is adjusted and a new stopping distance is calculated. This iterative procedure is repeated until the difference between measured and calculated stopping distance is less than a specified tolerance.

5.1.4 Method 1D: In this method the average friction coefficient is calculated from measured brake torque and the moment of inertia of the wheels and tires according to the following equations:

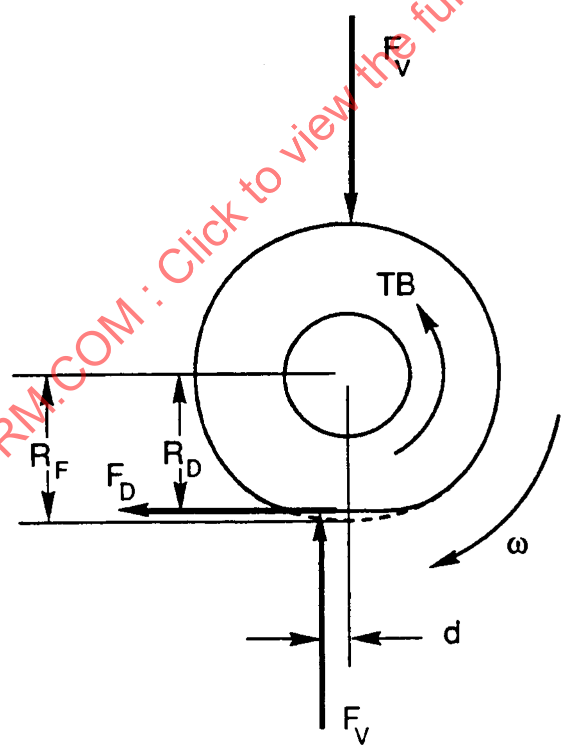

FIGURE 2 - Forces and Torques on a Braked Wheel

5.1.4 (Continued):

The following equation defines the balance of torques on a braked wheel as shown in Figure 2.

$$TB = F_D R_D + F_V d - I\dot{\omega} \qquad \text{(Eq. 7)}$$

where:

$\dot{\omega}$ = Wheel angular acceleration
I = Wheel and tire moment of inertia
R_D = Deflected tire radius
R_F = Free tire radius
T_B = Brake torque
F_V = Wheel vertical load
F_D = Wheel drag load
d = Tire footprint center of pressure shift

The tire footprint center of pressure shift can be defined as

$$d = \frac{F_D}{k} \qquad \text{(Eq. 8)}$$

where:

k = Tire spring constant

When Equation 8 is substituted into Equation 7, the following relationship is defined:

$$F_D = \frac{(TB + I\dot{\omega})}{\left(R_D + \frac{F_V}{k}\right)} \qquad \text{(Eq. 9)}$$

A possible approximation of Equation 9 would be:

$$F_D \approx \frac{(TB + I\dot{\omega})}{\left(1 - \frac{\mu_R}{\mu_D}\right)R_F}, \mu_D > \mu_R \qquad \text{(Eq. 10)}$$

where:

μ_R = Rolling resistance friction coefficient
μ_D = Drag force friction coefficient

A typical value of the rolling resistance μ_D might be 0.02, and for a braking effort near the tire skid point, the denominator of Equation 10 is approximately equal to 0.95 R_F.

5.1.4 (Continued):

The average coefficient of friction is then defined by the following equations:

$$\mu = \sum_{i=1}^{NB} \left(\frac{F_{D_i}}{F_{V_i}} \right) \quad \text{(Eq. 11)}$$

$$\mu_A = \frac{1}{t_A - t_R} \int_{t_A}^{t_R} \mu \ dt \quad \text{(Eq. 12)}$$

where:

NB = Number of brakes
μ = Instantaneous friction coefficient
μ_A = Average friction coefficient
t_A = Time of brake application
t_R = Time of brake release

Implementation of this method involves instrumentation to measure wheel speeds and accelerations, brake torque, and main-gear wheel loads.

5.1.5 Method 1E: Drag Force/Torque/Pressure Efficiency: As an alternative to stopping distance performance, efficiency calculations based on measured parameters can be made for those aircraft tests which include direct measurements of drag force, brake torque, or brake pressure. For this method the drag force, brake torque, or brake pressure curves should be integrated from brake application to brake release to get the actual area under the curve. The peaks (not transients) of the curves may be connected and integrated to get the optimum area under the curves. The efficiency of braking is defined as the ratio of the actual area divided by the optimum area as shown in Figure 3.

A better approximation can be made by using a velocity-weighted summation. Thus summation is done by multiplying both measured and peak values of drag force, brake torque, or brake pressure by velocity before the integration is performed.

For this method of estimating antiskid braking performance, the drag force curve would be the first choice for analysis. If this parameter is not available, then the brake torque curve or the brake pressure curve may be substituted. Antiskid braking performance estimates based on the brake pressure curve will probably be the least accurate in this group.

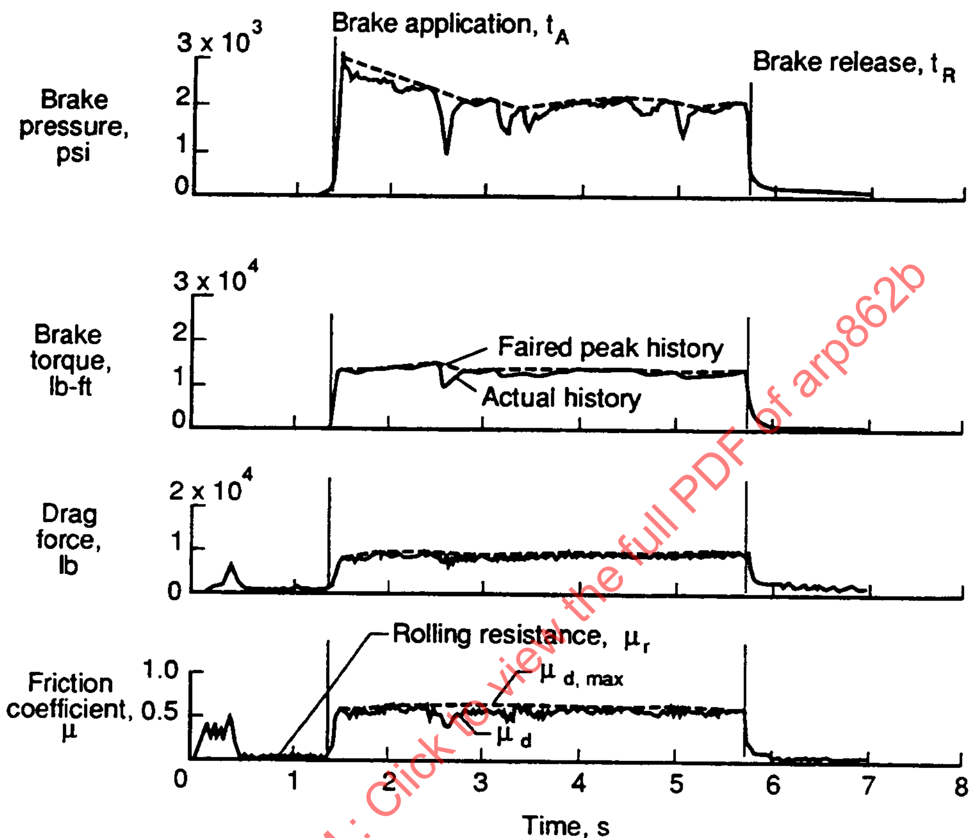

FIGURE 3 - Brake Pressure, Brake Torque, Drag Force, and Friction Coefficient Time Histories. Dry Runaway, 40 x 14 Aircraft Tire, Speed = 99 Knots, Tire Vertical Load = 13 900 lb

5.2 Simulator Tests:

Methods described in 5.1 can be used for performance evaluation to match the simulator. The simulator can then be used to assess and tune the antiskid system. The availability and controllability of variables not measurable on aircraft tests allow direct calculation of antiskid system efficiency on a computer simulator. Several efficiency calculation methods are available on a simulator as described in the following paragraphs.

5.2.1 Method 2A: Stopping distance efficiency is the ratio of the minimum distance required by the aircraft to stop for a given condition and the actual distance required to stop. Stopping distance efficiency is calculated by first conducting a simulated stop with the antiskid system off and the friction force held equal to the maximum available friction coefficient times the instantaneous vertical tire load. This defines the perfect stopping distance. A stop is then made with the antiskid system active to define the actual stopping distance. The efficiency is then obtained by dividing the perfect stopping distance by the actual stopping distance. This method is described in Reference 2.1.3 and is defined by Equation 13:

$$\eta = \frac{X_{perfect}}{X_{actual}} \times 100 \qquad \text{(Eq. 13)}$$

where:

η = Stopping distance efficiency
$X_{perfect}$ = Minimum aircraft stopping distance
X_{actual} = Actual aircraft stopping distance

NOTE: When the simulation assumes a constant deceleration stop, then the perfect stopping distance can be defined by Equation 14:

$$x_{perfect} = \frac{\dot{x}_0^2}{2\mu_{max}g} \qquad \text{(Eq. 14)}$$

where:

μ_{max} = Maximum available friction coefficient
g = Acceleration of gravity
$\dot{x}_0$ = Initial aircraft velocity

5.2.2 Method 2B: Developed μ efficiency is the ratio of the average friction coefficient actually developed during the stop and the average available friction coefficient. The developed μ efficiency is calculated as follows:

a. Calculate the instantaneous actual and available friction coefficients by dividing the instantaneous braking forces by the instantaneous vertical main gear loads.

b. Calculate the distance-weighted average actual and available friction coefficients for the entire stop by using the instantaneous friction coefficients in the equation below:

$$\text{Distance-weighted average } \mu = \frac{1}{S} \int \mu_1 \, ds \qquad \text{(Eq. 15)}$$

$$\mu = \frac{1}{S} \int \mu_1 V_i \, dt \qquad \text{(Eq. 16)}$$

where:

μ_i = Instantaneous μ
v_i = Instantaneous velocity
S = Total stopping distance

c. Calculate the developed efficiency by dividing the distance-weighted average actual friction coefficient by the distance-weighted average available friction coefficient.

This method is depicted graphically in Figure 3. The dashed line in the friction coefficient time history represents the maximum available friction coefficient to the antiskid system and the area under the dashed curve divided by the time increment between brake application and brake release represents the average peak coefficient available to the antiskid system during the braking effort. The solid curve in the friction coefficient time history represents the instantaneous friction coefficient developed by the antiskid system during the braking effort and the area under that solid line divided by the duration of braking activity represents the average friction coefficient developed by the system over the braking effort. The ratio obtained by dividing the area under the solid line by the area under the dashed line is a measure of the antiskid system efficiency.