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Superseding AIR1739

Information on Antiskid Systems

INTRODUCTION

The summary of experience in antiskid system usage will be used by design personnel to avoid the pitfalls experienced by others in application of antiskid to retrofitted and new systems. The information will be presented as General System Description and Operation, Hardware Details and Functions, System Performance Evaluation, System Development Process, and Service Problems.

Need and Requirements:

While antiskid system, component, and feature problems and limitations are well known to the designer and specific user, there is no documentation available which describes the broad field of applications. This document is a compendium of field experience and can form the basis for establishing system requirements. The requirements should reflect the intended operating surfaces, the desired performance, required system efficiency and the method of determining this efficiency. Required system characteristics or features should be initially established along with performance requirements prior to contracting for a system.

The need for a skid control system is a function of the ability, or rather the inability of the pilot to maintain control of the brake system and to avoid inadvertent wheel lockup and possible tire failure. With most power brake systems, the "feel" of the overall aircraft system to the pilot is inadequate to maintain knowledge of the state of rotation of all the aircraft wheels. This is especially true for large multi-wheel aircraft. Therefore, some degree of assistance is needed to detect an adverse condition. This is considered a basic need resulting in the inclusion of an antiskid system. In addition to this basic situation, it may be additionally desirable to have a system which will assist the pilot in achieving optimum stopping performance.

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1. SCOPE:

This SAE Aerospace Information Report (AIR) has been prepared by a panel of the SAE A-5A Committee and is presented to document the design approaches and service experience from various applications of antiskid systems. This experience includes commercial and military applications.

1.1 Purpose:

The purpose of this document is to describe antiskid system configurations, features, modes of operation and to define various methods used to calculate antiskid system performance.

2. APPLICABLE DOCUMENTS:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications:

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

ARP862A,	Skid Control Performance Evaluation (April 1996)
AS483	Skid Control Equipment (March 1992)
AIR764C	Skid Control System Vibration Survey (March 1993)
AIR1064C	Brake Dynamics (January 1997)
ARP1070B	Design and Testing of Antiskid Brake Control Systems for Total Aircraft Compatibility (November 1991)

2.2 U.S. Government Publications:

Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

14 CFR 25.735e	Antiskid Systems
14 CFR 25.109	Accelerate-Stop Distance
14 CFR 25.1301	Function and Installation
14 CFR 25.1309	Equipment, Systems and Installations
AC 25-7A	Flight Test Guide for Certification of Transport Category Airplanes
MIL-W-5013L	Military Specification Wheel and Brake Assemblies, Aircraft General Specification for (October 29, 1982)
MIL-PRF-5041J	Performance Specification, Tires, Ribbed Tread, Pneumatic, Aircraft, General Specification for (April 30, 1998)
MIL-B-8075D	Brake Control Systems, Antiskid, Aircraft Wheels, General Specification for (February 24, 1971)

2.3 Other Documents:

AFFDL-TR 74-118 “Test and Performance Criteria for Airplane Antiskid Systems," October 1974

Boeing Report D6-41115, "Research Study on Antiskid Braking Systems for the Space Shuttle," NASA Contract 8-27864

ASD-TR-74-41, FAA-RD-74-211, Vols. I and II, "Combat Traction II, Phase II," October 1974

ASD-TR-77-6, Vols. I and II, "An Extended Prediction Model for Airplane Braking Distance and a Specification for a Total Braking Prediction System," March 1977

NASA TP-1051, “Behavior of Aircraft Antiskid Braking Systems on Dry and Wet Runway Surfaces - A Slip-Velocity-Controlled, Pressure-Bias-Modulated System”, December 1979

3. GENERAL SYSTEM DESCRIPTION AND OPERATION:

3.1 General System Configuration:

Antiskid Control System is defined as a group of interconnected components which interact to prevent inadvertent tire skidding and contribute to shorter aircraft stopping distances by controlling excessive brake pressure. The basic system normally consists of a wheel speed transducer, a control circuit and a brake pressure control valve as shown in Figure 1. The antiskid system is a sub-system of the braking system which also includes the pilot control and parking brake functions, the automatic braking system, gear retraction braking and the wheel, tire and brake assembly. In some cases, the pilot’s control function uses the antiskid system hardware, as is the case in many brake-by-wire systems.

3.2 System Operation:

The basic purpose of the antiskid system is to limit pilot commanded brake pressure to levels compatible with optimum aircraft deceleration, while preventing excessive wheel skidding. Typical operation is as follows. The pilot applies brakes by applying force to the brake pedals resulting in an increase in pressure in the brakes. As the pressure increases, the wheel begins to slow down and the force between the tire and the runway increases. When the available friction force is exceeded, the wheel begins to decelerate rapidly. This is sensed by the antiskid system which in response outputs a signal to reduce pressure. With release of pressure, the wheel accelerates to synchronous speed, the release signal is removed and pressure is reapplied. This sequence then repeats as needed.

3.3 Antiskid Control Classification:

Many different antiskid systems are in use today. They represent a broad spectrum of an evolving technology from the late 1940's and different approaches to the solution of a complex problem. The very early systems utilize on-off control concepts, while later systems provide different degrees of brake pressure modulation in response to wheel speed changes.

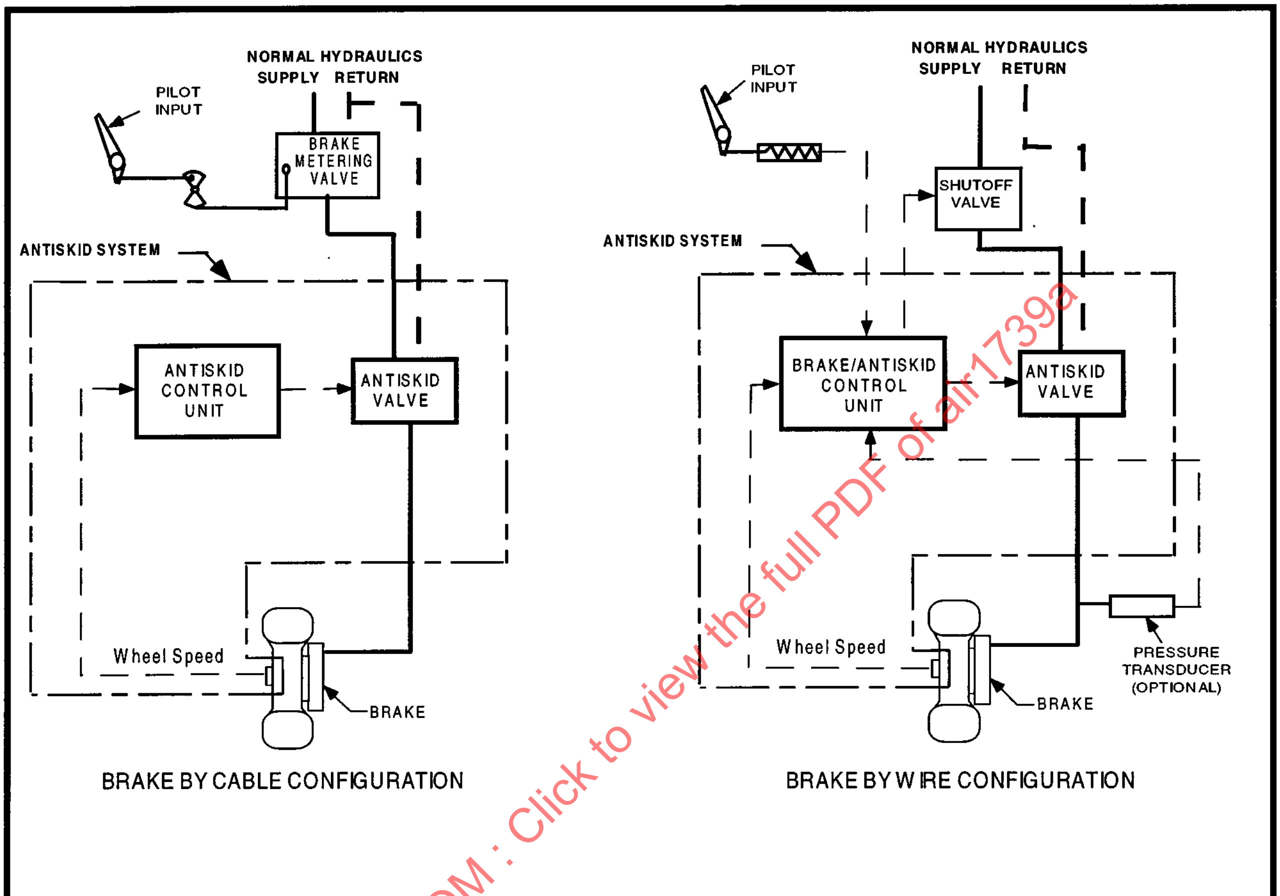


FIGURE 1 - Antiskid System Schematic

3.3.1 ON-OFF System: A typical on-off system is in use on the B-52 and consists of three components: a skid and locked wheel detector, a control shield, and a solenoid valve. The detector is an electro-mechanical 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.

The detector is the heart of this antiskid system. Its function in the system is to detect wheel decelerations above a preset value. As implemented in the B-52, the detector is mounted in the axle and is driven by wheel hub cap rotation. The skid sensing portion of the detector consists of an inertia flywheel and an overload-release clutch. The flywheel's inertia causes the spring loaded clutch to release when wheel deceleration exceeds a predetermined rate. Because the wheel is slowing down faster than the released inertia, a relative displacement occurs between the inertia and the drive, attached to the wheel, causing a set of electrical points to contact, thereby completing the skid circuit to the control shield. The shield in turn provides an electrical signal to the antiskid solenoid valve, resulting in a release of brake pressure.

As the wheel accelerates back to synchronous speed, the contacts in the detector open, removing the signal from the antiskid solenoid valve. Thus, the pilot's metered pressure is again applied to the brake, allowing the skid cycle to repeat. In this type of system, the pilot must adjust the applied pressure level to minimize cycling in order to achieve good performance. Figure 2 shows an example of typical control using an ON-OFF system on a dry and a wet runway.

3.3.2 Modulating System (Quasi-Modulating): Modulating antiskid systems 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.

The first generation modulating systems, generally, act to release brake pressure when the computed wheel deceleration exceeds a preset value indicating an incipient skid. Brake pressure is held off for a time duration depending on the depth of the skid. As the wheel recovers from the skid, brake pressure is first stepped up to a low value and then gradually increased until a new incipient skid is sensed. During the wheel skid essentially all corrective action is based on a pre-programmed sequence, rather than the wheel speed/time history. These modulating systems can be tuned to provide very good dry runway performance; however, on slippery runways they are only able to extract a fraction of the maximum available friction because too much time is consumed in opening and closing the brake stack. The control dynamics of the modulating systems are not optimized for maximum performance on slippery runways. Figure 3 shows an example of typical control for a Modulating System on a dry and a wet surface.

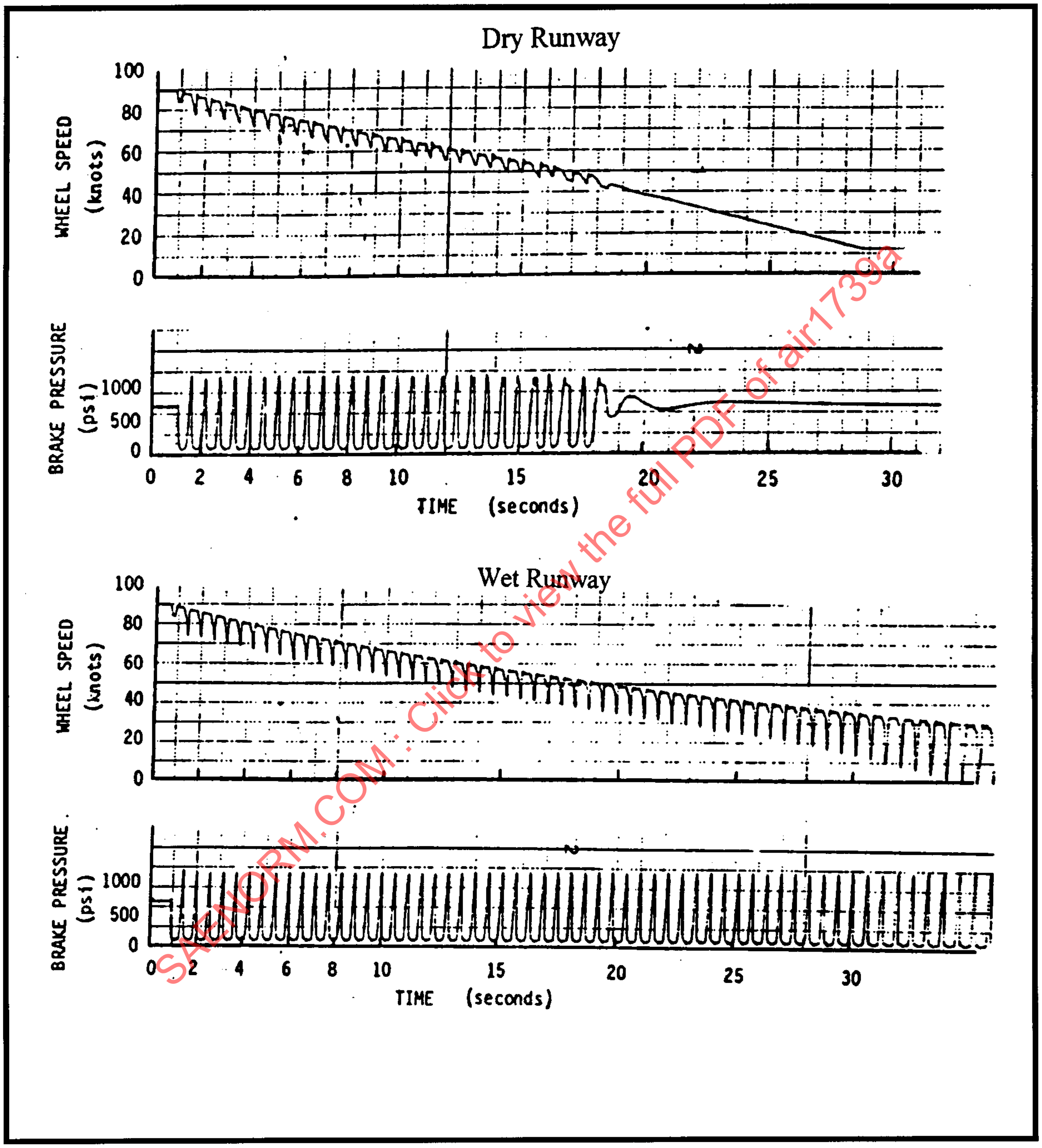


FIGURE 2 - On-Off System Operation

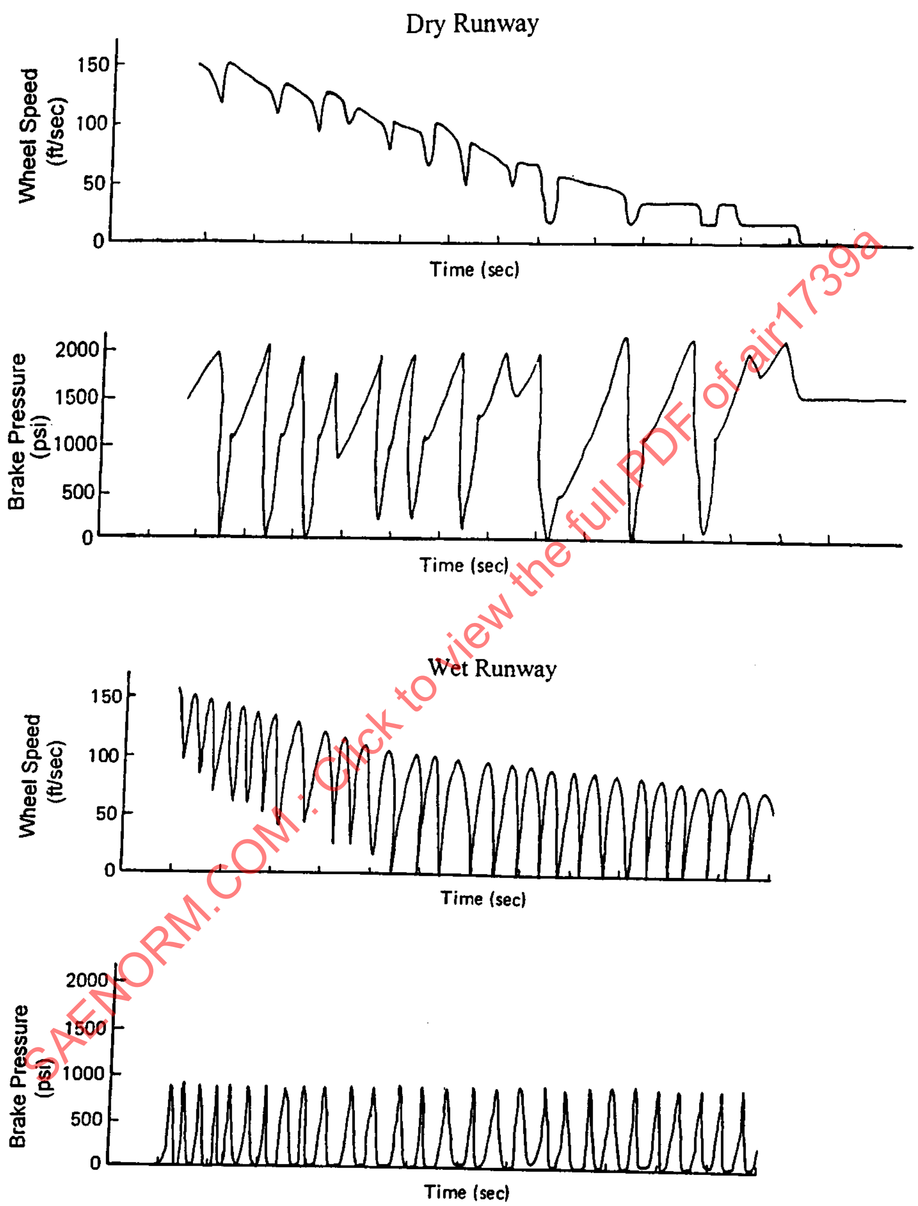


FIGURE 3 - Modulating System Operation

3.3.2 (Continued):

Most modulating systems rely on an electronic circuit for intelligence. However, one system is in use which consists of only two hydro-mechanical components. A hydraulic modulator, upstream of the brake, controls initial pressurization volume and pressure application rate. The sensor, downstream of the brake, is located in the wheel axle and controls pressure release rate when an incipient skid is sensed.

3.3.3 Adaptive Systems (Fully Modulating): Adaptive antiskid systems 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.

Adaptive systems, typically, compare braked wheel speed to a reference wheel speed. In almost all systems the reference wheel speed is derived electronically from the braked wheel during spin-up and brake release. However, one system is in use which measures the reference wheel speed with a separate and additional sensor in the nose wheel. The control circuit cycles the braked wheel about a fixed slip ratio Slip (or slip ratio) is defined as one minus the wheel rotational speed divided by the wheel rotational speed of a free rolling wheel. Figure 4 shows an example of typical control for an Adaptive system on a dry and a wet runway.

3.4 Control Features:

Experience has shown that several ancillary functions contribute to making the system work under all circumstances. These include wheel control grouping, touchdown protection, locked wheel protection, and fault detection.

3.4.1 Individual Wheel Control: Individual wheel control is a system configuration in which each braked wheel is controlled by a separate valve and control circuit. Individual wheel control is the predominant control configuration in use because of its high efficiency.

3.4.2 Paired Wheel Control: In a paired wheel control configuration, two or more brakes are controlled together utilizing one valve and control circuit This configuration, while not as efficient as individual wheel control, has been used to assist in maintaining directional control where individual control can produce yaw moments which are difficult to control by the pilot. Paired wheel control has been used for the backup system on large aircraft with multiple braked wheels on each gear to reduce the amount of hardware required with only a small loss in performance.

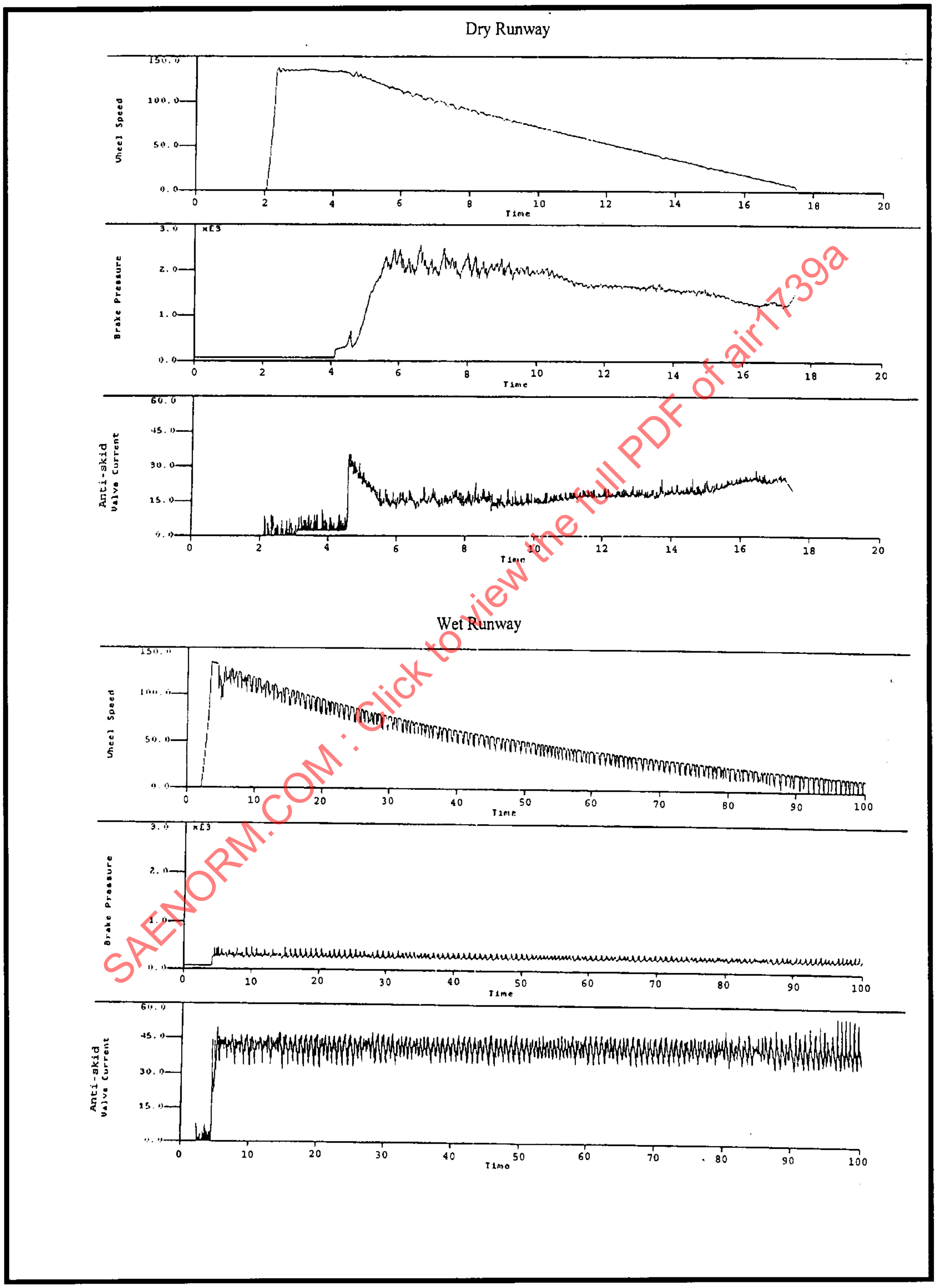


FIGURE 4 - Adaptive System Operation

3.4.3 Locked Wheel Protection: Generally all antiskid systems for modern jet aircraft incorporate a locked-wheel protection feature. The wheel speed signals, on two (or more) wheels, are used to produce an “airplane moving” reference. In the event one of the wheels should lock up, a comparison of that wheel speed with the reference signal provides a basis for the release of the brake pressure of the slow wheel. A reference memory may be provided to maintain the reference should the two (or more) wheels lock up at the same time. The combination/location of wheels grouped (or paired) for locked wheel protection should be selected on the basis of airplane configuration, antiskid system configuration and failure modes. Typical pairing used include: inboard and outboard wheels across the airplane, adjacent wheels on a landing gear, and fore/aft wheel pairs on a truck (4-wheel bogie).

3.4.4 Touchdown Protection: The purpose of touchdown protection is to make sure that braked wheels are free to rotate at touchdown even though the pilot had inadvertently applied brakes. The protection is normally implemented using the wheel speed signal and a signal from the airplane’s AIR/GROUND logic system. If the AIR/GROUND signal indicates that the airplane is in the air and the wheel speed is lower that a preset level, a full dump signal is applied to the antiskid valve. A transition from air to ground indication will result in removal of the dump signal, normally after a delay to allow wheel spin-up. Spin-up of the wheel to a level higher than the preset level will also remove the dump signal even with an airplane in the air indication.

3.4.5 Hydroplaning Protection: Hydroplaning Protection provides an extended release of pressure to a braked wheel which fails to spin up due to hydroplaning at high speed on a flooded runway. Hydroplaning protection is implemented by the use of an airplane ground speed reference which is external to the antiskid system, such as an Inertial Reference/Navigation System. Brake release is based on the wheel speed being less than a set percentage of the ground speed reference. The hydroplaning protection would also provide the touchdown protection feature.

3.4.6 Fault Detection: Antiskid systems normally contain fault detection capability to provide indication to the pilot that the system is not fully operational, so that the pilot can use appropriate stopping techniques and allow for timely maintenance actions. At the simplest, the fault detection may do nothing more than check continuity to valves and wheel speed transducers and the availability of power. More sophisticated systems run end to end checks to ensure the health of the system and to isolate problems to the line replaceable unit (LRU) level or lower.

4. HARDWARE DETAILS AND FUNCTIONS:

A discussion and description of the hardware components more frequently encountered in antiskid systems is included as an aid in understanding overall system operation. For the sake of brevity, only the more commonly used components will be discussed.

4.1 Wheel Speed Transducer:

The purpose of the wheel speed transducer is to provide an electric signal equivalent to the angular speed of the braked wheel. The transducer is mounted in the wheel axle and must be rugged in design to withstand high linear and torsional accelerations. Two basic transducers are in use, the AC Generator and the DC Generator. Fiber optic based wheel speed transducers have been developed and will be entering service on a military aircraft.

4.1.1 DC Generator: The DC Generator produces a voltage proportional to wheel speed. The device is completely self-contained and is mounted in the axle. The armature of the generator is attached to the wheel and rotates with it. The basic parts of the transducer as shown in Figure 5 are a permanent magnet, armature, commutator, and brush assembly. Rotation of the commutator in the magnetic field induces an electrical signal proportional to wheel speed.

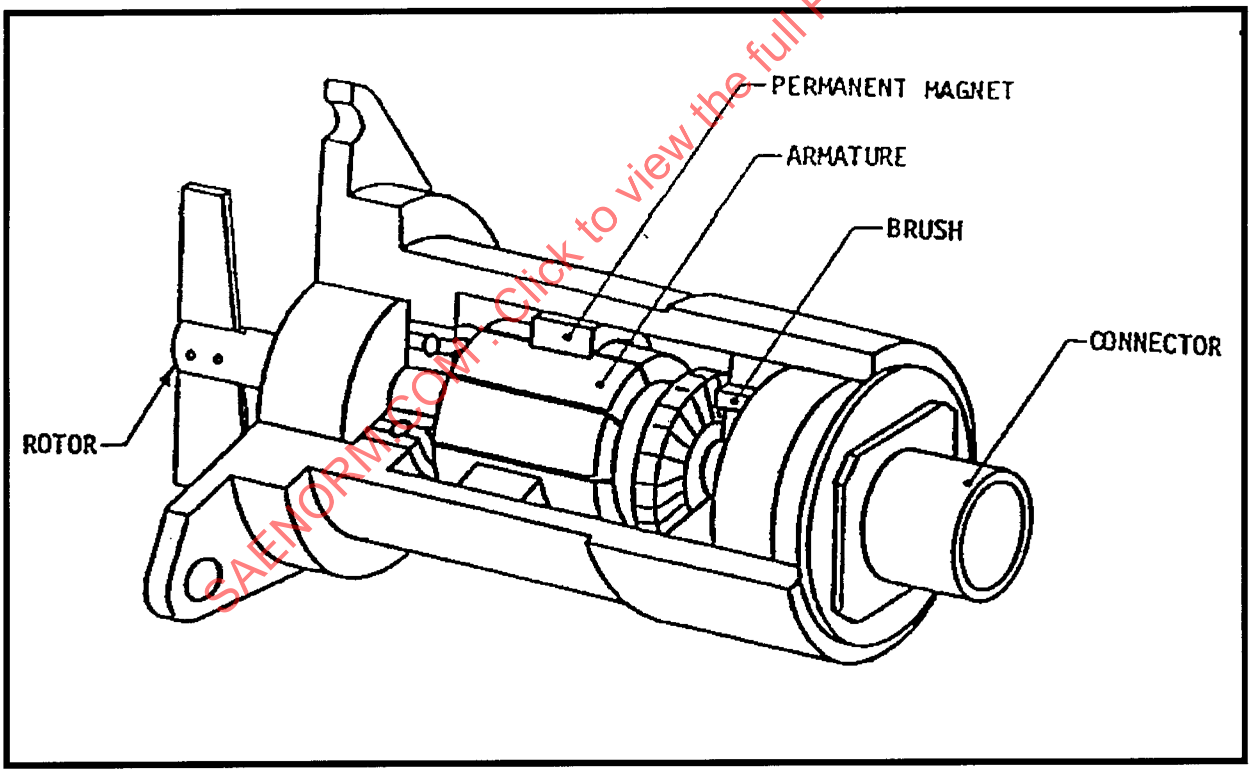


FIGURE 5 - DC Wheel Speed Transducer

4.1.2 AC Generator: The AC Generator is similar in appearance to the DC Generator but contains no brushes. The AC Generator produces an output voltage signal with amplitude and frequency proportional to rotational speed and number of rotor teeth. A magnetic field is generated either with a DC current or a permanent magnet. As the rotor turns, the alternating alignment and misalignment of the teeth in the rotor and the stator vary the reluctance in the magnetic current. This results in an alternating current with frequency proportional to wheel speed. A typical AC wheel speed transducer is shown in Figure 6.

4.1.3 Fiber-Optic Wheel Speed Transducers: Fiber-optic wheel speed transducers use light signals rather than electrical signals. A light source is normally located in the control unit and the light is transmitted through the transducer and back to a detector in the control unit via fiber optic cable. Within the transducer, the light is interrupted by a rotating means producing a detected signal with a frequency proportional to wheel speed.

4.1.4 Wheel Speed Transducer Couplings: The function of the transducer coupling is to connect the rotor of the wheel speed transducer to the rotating wheel, normally the wheel hubcap. In doing so, it must compensate for any misalignment between the axle centerline and the rotational axis of the wheel. The normal method used is to have a drive arm mounted on the transducer shaft that fits in a radial slot in the part mounted in the hub cap. Figure 7 shows a spider/dog-bone coupling using this method. A shortcoming of this method is that if there is misalignment between the two axis, a one cycle per revolution sine wave is imposed on the wheel speed due to the varying arm length.

Another coupling currently in use is a bellows coupling, Figure 8. This coupling will accommodate large offsets, both angular and radial, with minimal effect on the signal quality.

An alternate approach is the use of a sensor/exciter ring configuration. In this configuration, an exciter ring is mounted in and rotates with the hubcap. The exciter ring has teeth that line up with teeth on a stationary sensor mounted in the axle. A sensor and exciter ring are shown in Figure 9.

4.2 Controller:

The control circuit is the brain of the antiskid system. Normally several functions are provided, regardless of the detail of the control concept. These functions include conversion of the AC wheel speed signal, computation, and valve current generation. In addition, locked wheel protection and built in test features are provided.

When an AC wheel speed sensor is used, the frequency content of the sensor output must be converted to a value representative of wheel speed, either a DC voltage in analog circuitry or a digital word in microprocessor based controllers. The use of an AC sensor yields better signal fidelity and improved noise immunity than the DC generator as long as a sufficient number of teeth are used on the rotor. The computational section of the circuit utilizes a number of control functions which are designed to command the maximum tire-runway friction coefficient regardless of airplane weight, speed, or runway condition. Manufacturers utilize different computational concepts to meet this basic requirement. A valve driver is required to amplify low level voltages from the computational circuits to current levels required by the antiskid valve. Proper valve driver design can reduce the induction lag of the valve.

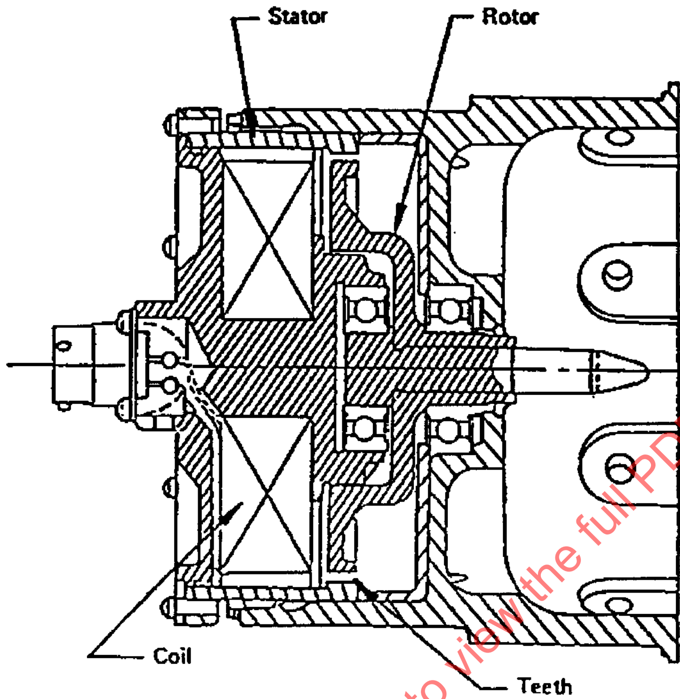


FIGURE 6 - AC Wheel Speed Transducer

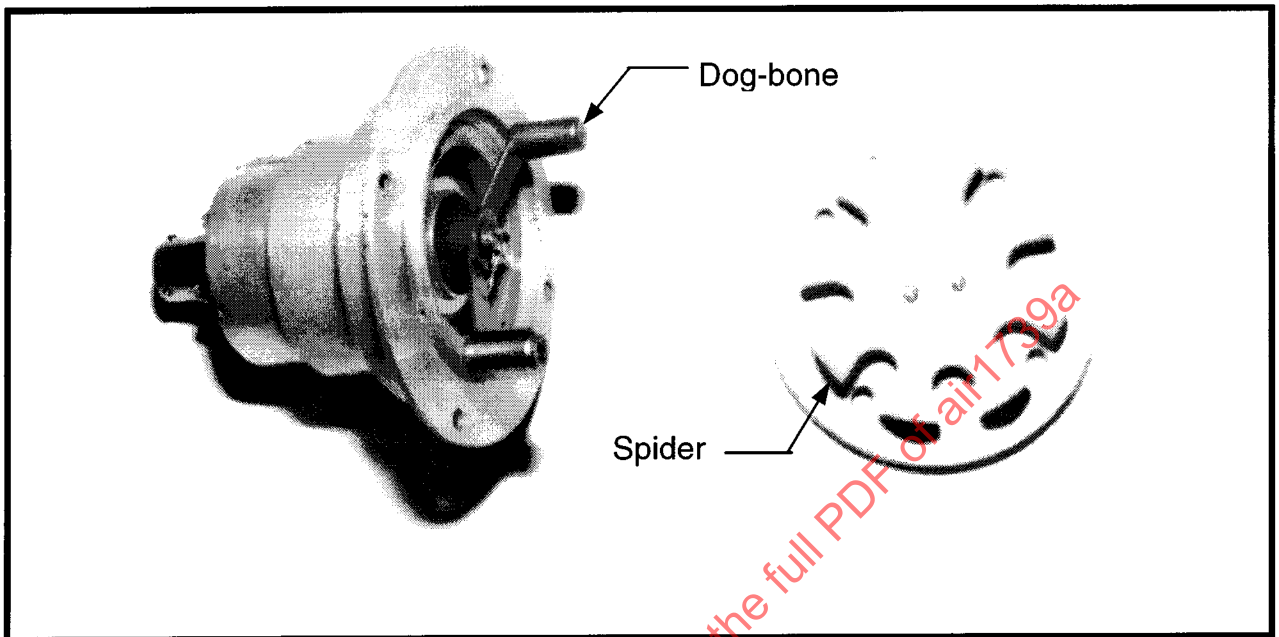


FIGURE 7 - Spider/Dog-bone Coupling

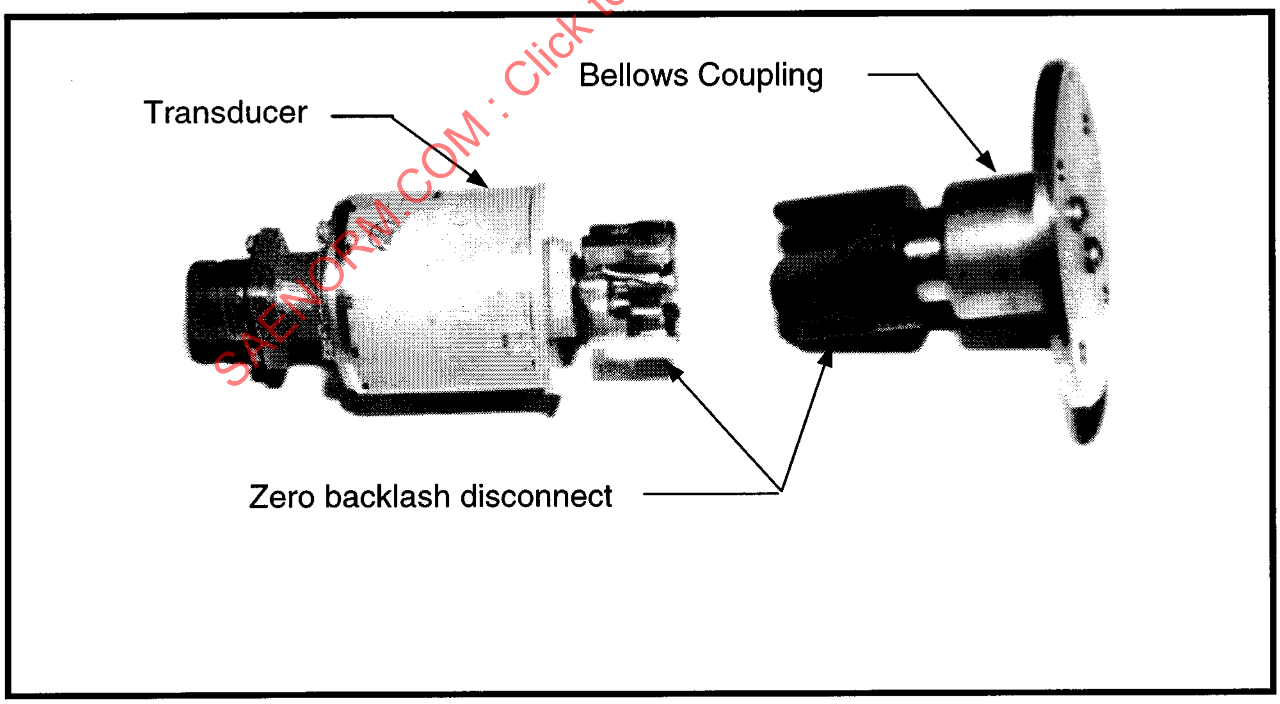


FIGURE 8 - Bellows Coupling

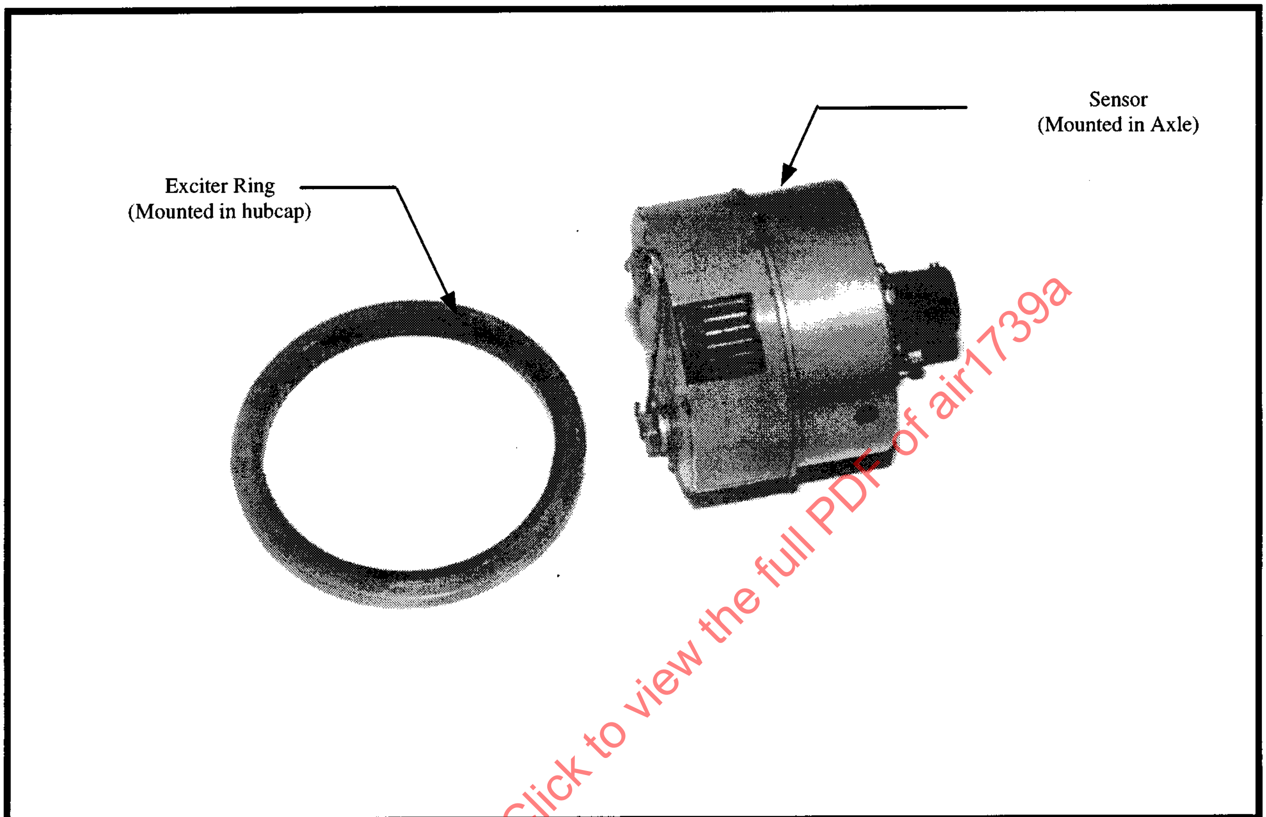


FIGURE 9 - Sensor - Exciter Ring

4.2 (Continued):

In the past, the control functions have been implemented as electronic analog circuitry. Many of the newer systems have gone to microprocessor based (digital) controllers, in which the functions within the controller are implemented in a program that executes on the microprocessor. This approach has allowed the implementation of more complex control functions and has improved system efficiency over the range of operation. Use of microprocessor based systems allowed improved fault detection within the system.

4.3 Antiskid Valve:

The antiskid valve is the interface between the low power electronic control circuit and high power hydraulic brake system.

A schematic of a typical antiskid valve is shown in Figure 10. The typical antiskid valve is a two-stage valve with a flapper/nozzle first stage and spool and sleeve second stage. A permanent magnet torque motor in the first stage operates the flapper. Both 3-way and 4-way first stage valves are used. The application of an electrical signal to the torque motor from the skid control box causes the flapper to move from the neutral position (maximum pressure). Movement of the flapper unbalances the bridge, with a resultant pressure differential applied to the second stage spool. Movement of the flapper from the relaxed position serves to reduce pilot metered pressure to the brake. The forces on the spool work to position it until an equilibrium position is reached. The output of the antiskid valve provides the control pressure to the brakes. Because of fail-safe requirements the valve is normally designed to port the pressure commanded by the pilot to the brake when no current is present. As current is increased, the valve reduces the brake pressure.

4.4 Brake and Tire:

The hydraulic brake is normally a multi-stator and rotor disk type designed to absorb the kinetic energy of the airplane. A sectional view of a typical steel brake and a typical carbon heatsink brake for use on a jet transport plane is shown in Figure 11. Hydraulic pressure is converted into a mechanical force with the pistons located peripherally in the brake housing, around the axle. As brake pressure is applied, the rotors and stators are forced together and against the backing plate. The resulting brake torque is a function of the applied pressure. High brake temperatures can cause fading of brake torque, while at low speed torque can increase rapidly. As brake linings wear, automatic adjusters provide for a stroke limit of the pressure plate to minimize piston free travel. A small amount of oil volume is required to pressurize the brake to full system pressure through the full range of brake wear.

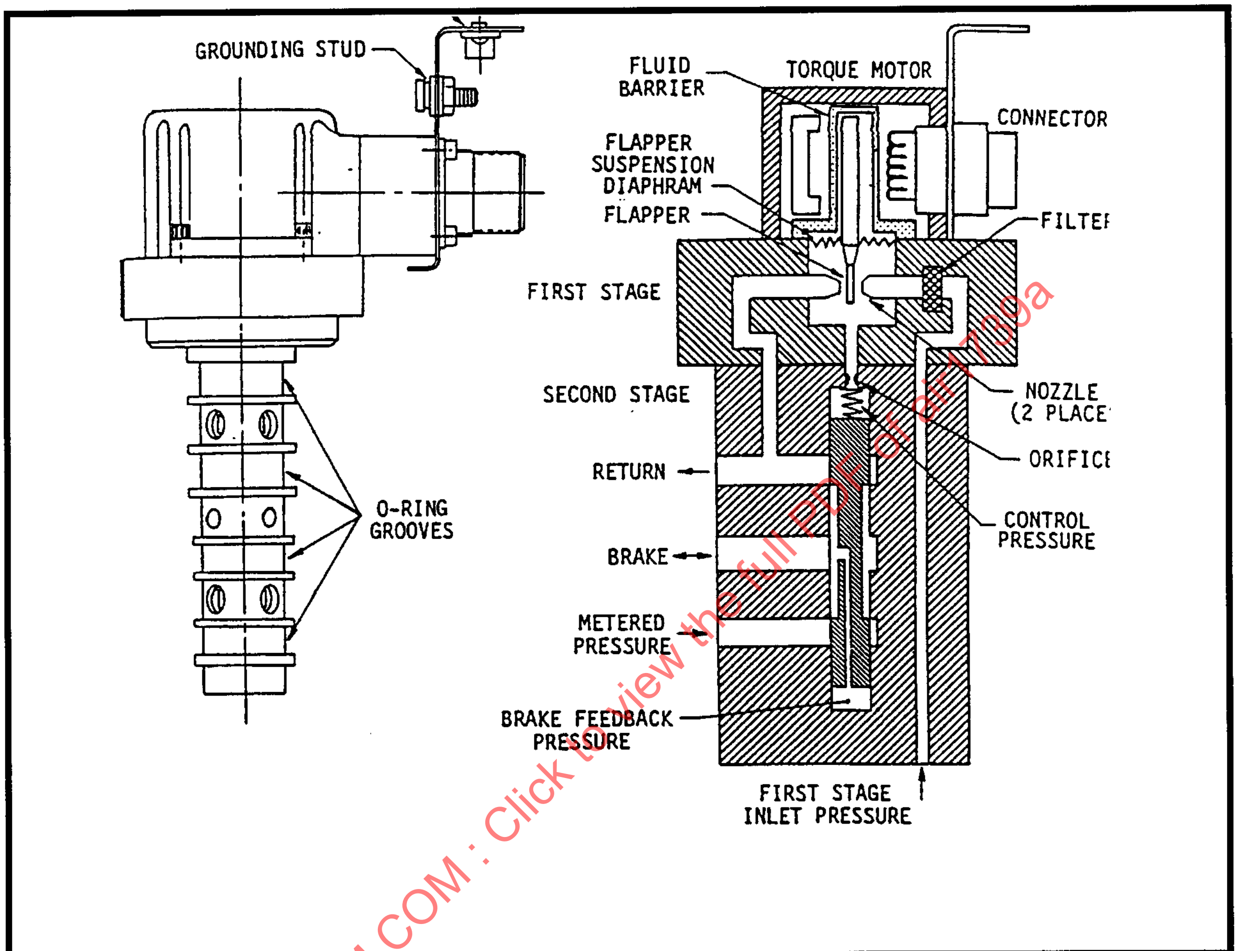
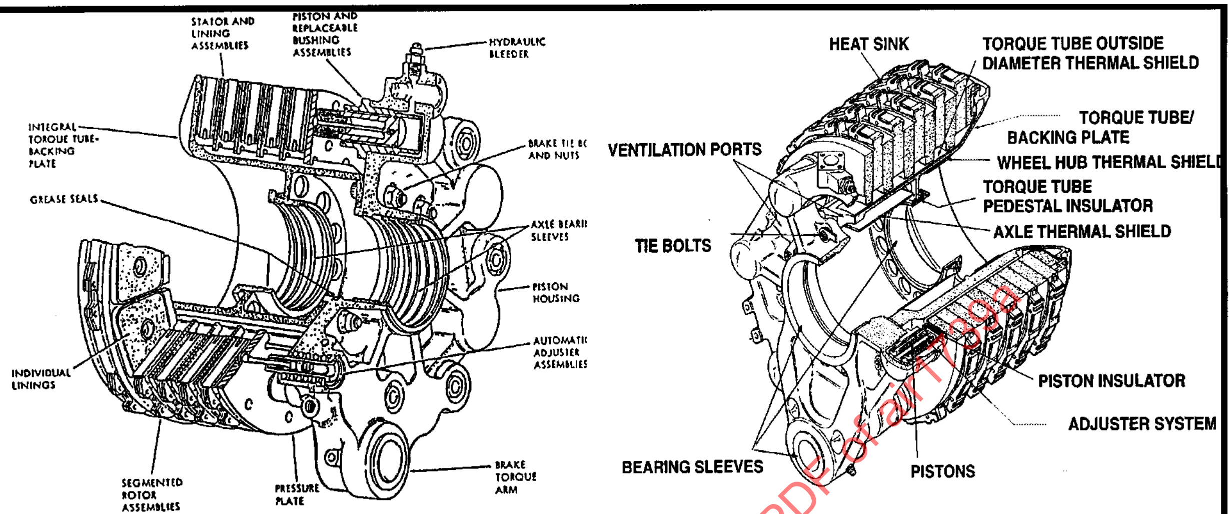


FIGURE 10 - Antiskid Servo Valve



a. Steel Heatsink Brake

b. Carbon Heatsink Brake

FIGURE 11 - Typical Aircraft Brake Assemblies

4.4 (Continued):

The tire, in conjunction with the runway generates the retarding friction forces as the brake is pressurized and provides a critical function in stopping the aircraft. Friction is generated at the interface between the ground and the tire footprint by forcing the wheel to rotate slightly slower than the ground speed demands. As the speed difference increases, friction forces increase accordingly. On dry pavements tire heating plays a dominant role in limiting friction. As the speed difference increases beyond the 15% slip point, friction decreases continuously all the way to lock up. Slip is defined as one minus the ratio of linear wheel speed (angular wheel speed times the rolling radius) to the ground speed. On wet pavements tire heating plays a less dominant role and friction stays nearly constant beyond the 15% slip point.

Aircraft tires also provide the distribution of gear load into the ground and the generation of side forces for directional control. The cross section of a typical aircraft tire is shown in Figure 12. Aircraft tires must operate over a wide temperature range. Compared to automotive tires they run at much greater deflection, usually 30 to 35% deflection of the section height. The side wall does not provide much stiffness by itself. The wheel serves to complete the toroidal pressure vessel and the inflation pressure, which can range from 45 psi to over 450 psi depending on application, provides much of the tire load bearing characteristics.

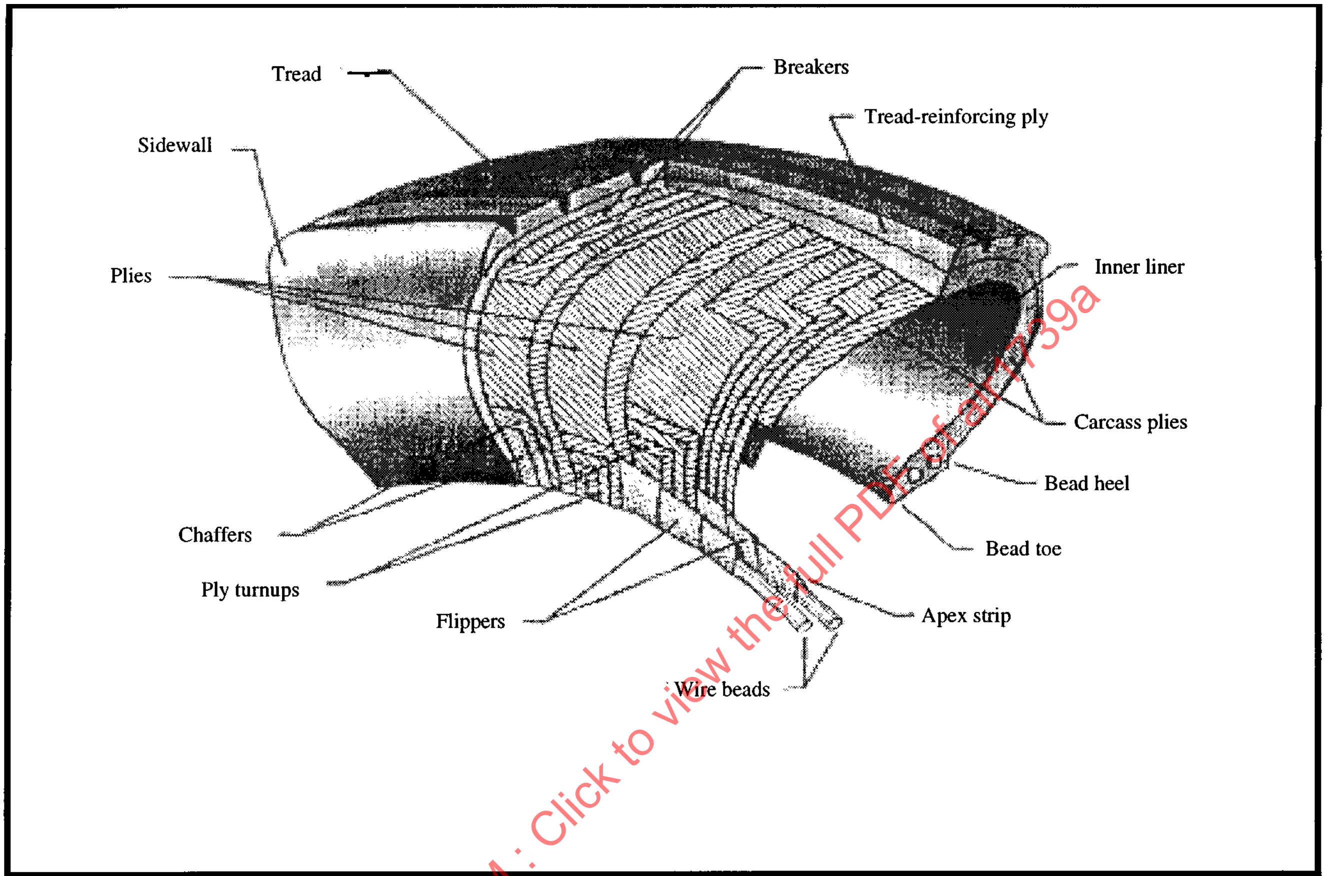


FIGURE 12 - Typical Aircraft Tire Construction (Bias)

5. SYSTEM PERFORMANCE EVALUATION:

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 Average Friction Coefficient Calculation - Basic Method: The average friction coefficient is calculated by dividing the average braking force by the average vertical load on the braked wheels. The first step is calculating an average braking force. This can be done in several ways as indicated in Alternate Methods 1-3.

In the basic method average braking force is calculated from brake energy. The average braking force is obtained by recording the instantaneous values of the brake torque and wheel rotational speed 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.

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

where:

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

The net brake energies from all the wheels are summed (Equation 2) and the average braking force is obtained by dividing the total energy by the measured stopping distance (Equation 3). This method does not account for the energy absorbed by the tire and the wheel bearing rolling resistance is assumed to be negligible. Measurement of brake torque may include errors due to frictional losses. Correction for these losses should be considered.

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

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

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

5.1.1 (Continued):

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 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.

$$\mu_A = \frac{FBA}{(WT - LIFT_A - F_N)} \quad \text{(Eq. 4)}$$

where:

μ_A = Average friction coefficient
WT = Aircraft weight
$LIFT_A$ = Average aerodynamic lift
F_N = Average load on unbraked nose wheels

The expression in the denominator of Equation 4 represents the load on the main-gear wheels (F_M). The relationship between main-gear wheel loads, aircraft geometry, and braking drag is illustrated in Figure 13 and the formula for the nose gear vertical load is given in Equation 5

$$F_N = \frac{(WT - LIFT_A) * X + A_H * FBA}{L} \quad \text{(Eq. 5)}$$

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 = Height of the center of gravity above ground contact
FBA = Braking force
F_M = Main-gear load
F_N = Nose-gear load

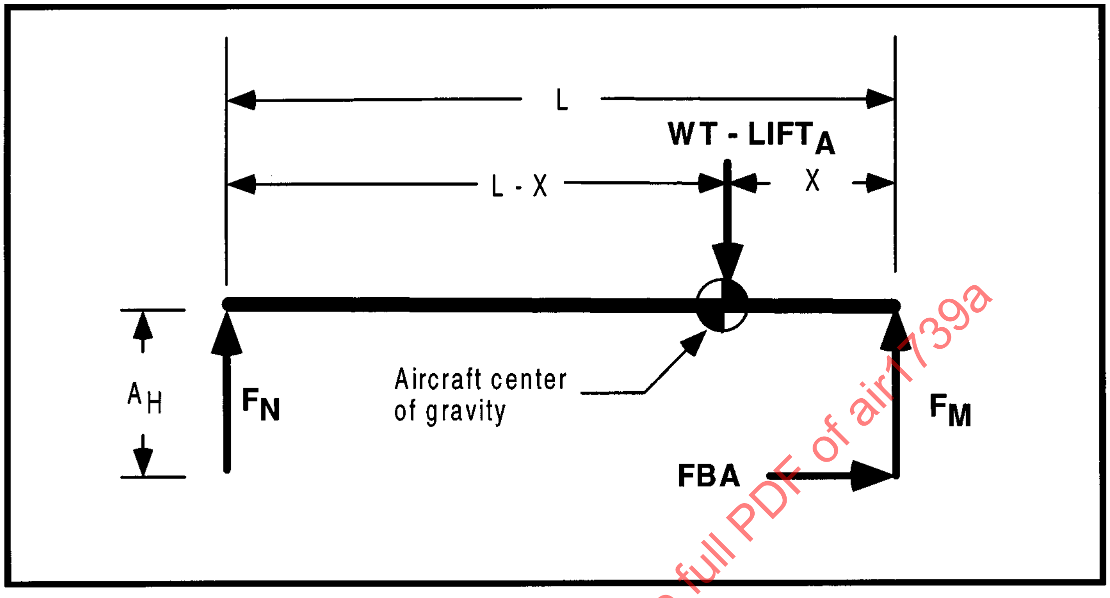


FIGURE 13 - Aircraft Landing Gear Geometry

5.1.2 Average Friction Coefficient Calculation - Alternate Method 1: This method is identical to the previous calculation method except that the percent of total energy absorbed by the brakes variable, PCEB, is introduce into Equation 3 to account for the energy absorbed by the tire, so that:

$$FBA = \frac{BET}{SB} \cdot \frac{100}{PCEB} \qquad \text{(Eq. 6)}$$

where:

PCEB = Percent of total energy absorbed by brakes

and FBA then becomes the braking force due to the brakes and tires. The value of PCEB must be determined from other testing or estimated. Some manufacturers consider the previous method to be a better indication of aircraft braking performance than this method.

5.1.3 Average Friction Coefficient Calculation- Alternate Method 2: 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 Equations 7 and 8:

$$\mu = \sum_{i=1}^{NB} \frac{\left(I \frac{d\omega_i}{dt} + TB_i \right)}{F_M R_H} \quad \text{(Eq. 7)}$$

$$\mu_A = \frac{1}{t_A - t_R} \int_{t_A}^{t_R} \mu \, dt \quad \text{(Eq. 8)}$$

where:

μ = Instantaneous friction coefficient
ω = Wheel angular speed
I = Wheel and tire moment of inertia
R_H = Deflected tire radius (axle height above ground contact)
NB = Number of brakes
TB = Brake torque
F_M = Main-gear load
t_A = Time of brake application
t_R = Time of brake release

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

5.1.4 Average Friction Coefficient Calculation - Alternate Method 3: 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 braking force, 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.

5.1.5 Antiskid System Efficiency Calculation - Drag Force/Torque/Pressure Efficiency Method: 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. Care should be taken in selection of the peaks to insure that they can be clearly identified as being coincident with a friction peak. The efficiency of braking is defined as the ratio of the actual area divided by the optimum area as shown in Figure 14.

A better approximation can be made by using a velocity-weighted summation. This 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. This approach addresses the fact that braking at high speed has a larger impact than braking at low speed.

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.

5.1.6 Antiskid System Efficiency Calculation - Wheel Slip Method: At brake application, the tire begins to slip with respect to the runway surface, i.e., the wheel speed slows down with respect to the airplane's ground speed. As the amount of tire slip increases, the brake force also increases until an optimal slip is reached. If the amount of slip continues to increase past the optimal slip, the tire will begin to skid, which reduces the braking force.

Using the wheel slip method, the antiskid efficiency is determined by comparing the actual wheel slip measured during a stop to the optimal slip. Since the wheel slip varies significantly during the stop, sufficient wheel and ground speed data must be obtained to determine the variation of both the actual wheel slip and the optimal wheel slip over the length of the stop. A sampling rate of at least 16 samples per second for both wheel speed and ground speed has been found to yield acceptable fidelity.

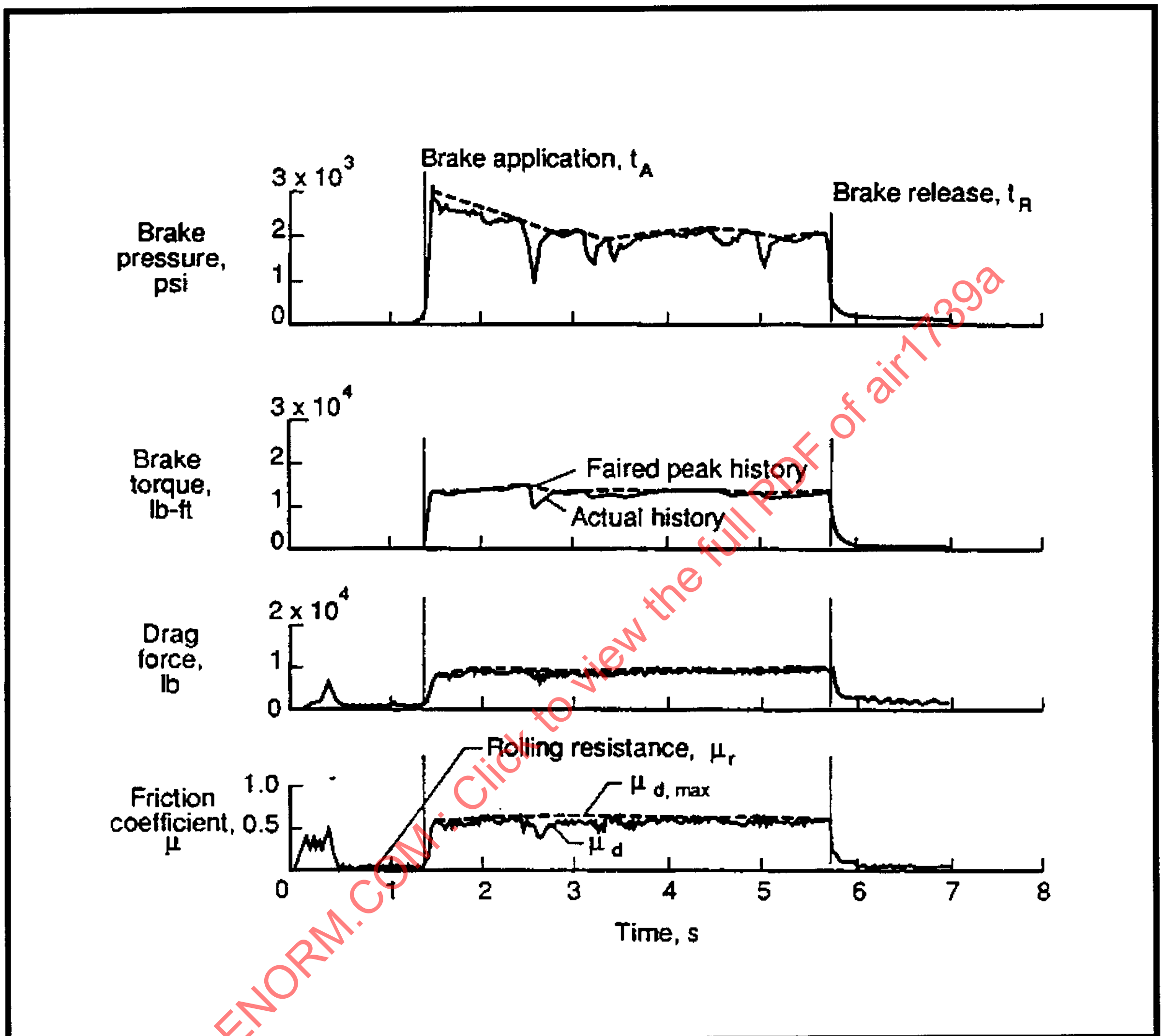


FIGURE 14 - Brake Torque/Pressure/Drag Force Efficiency

5.1.6 (Continued):

For each wheel and ground speed data point, the instantaneous antiskid efficiency value should be determined from the relationship shown in Figure 15.

for

$$\text{WSR} < \text{OPS Efficiency} = 1.5\left(\frac{\text{WSR}}{\text{OPS}}\right) - 0.5\left(\frac{\text{WSR}}{\text{OPS}}\right)^3$$

$$\text{WSR} = \text{OPS Efficiency} = 1.0$$

$$\text{WSR} > \text{OPS Efficiency} = 0.5\left(1 + \frac{(1-\text{WSR})}{(1-\text{OPS})}\right)$$

where:

$$\text{WSR} = \text{The wheel slip ratio} = 1 - \left(\frac{\text{Linear wheel speed}}{\text{Ground speed}}\right)$$

and OPS is the optimal slip ratio

The optimal wheel slip ratio value(s) (OPS) must be determined to use this method. A method for determining the optimal slip value(s) is to compare time history plots of the brake force and wheel slip data obtained during the stopping tests. If, during a skid, the wheel slip continues to increase after a reduction in the brake force, the optimal slip is the slip value corresponding to the brake force peak. Figure 16 shows an example of this. Note that both the actual wheel slip and the optimal wheel slip can vary during the stop. For brake installations where measuring brake force directly is impractical, brake force may be determined from other parameters (e.g., brake pressure) if a suitable correlation is available.

To determine the overall antiskid efficiency value the instantaneous antiskid efficiencies should be integrated with respect to distance and divided by the total stopping distance:

$$\text{antiskid efficiency} = \int \frac{\text{instantaneous efficiency}}{s} ds$$

where:

s = Stopping distance

The stopping distance is defined as the distance traveled during the specific runway stopping demonstration, beginning when the full braking configuration is obtained and ending at the lowest speed at which antiskid cycling occurs (i.e., the brakes are not torque-limited), except that this speed need not be less than 10 knots.

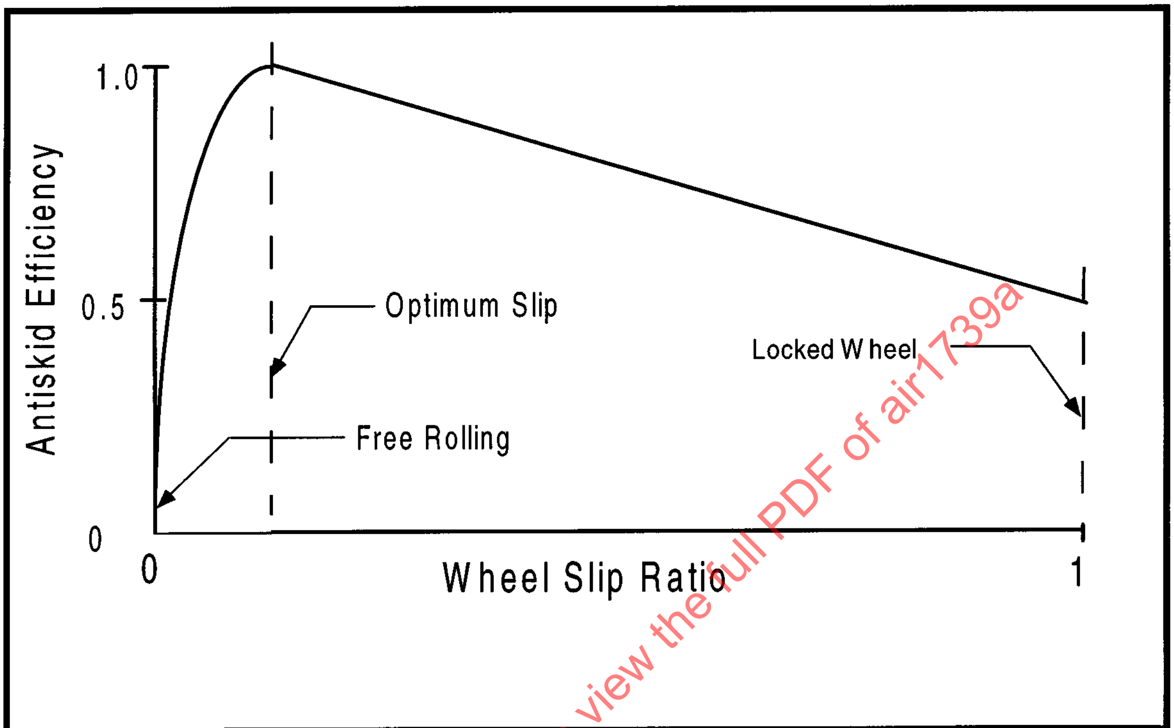


FIGURE 15 - Antiskid Efficiency Versus Wheel Slip Ratio

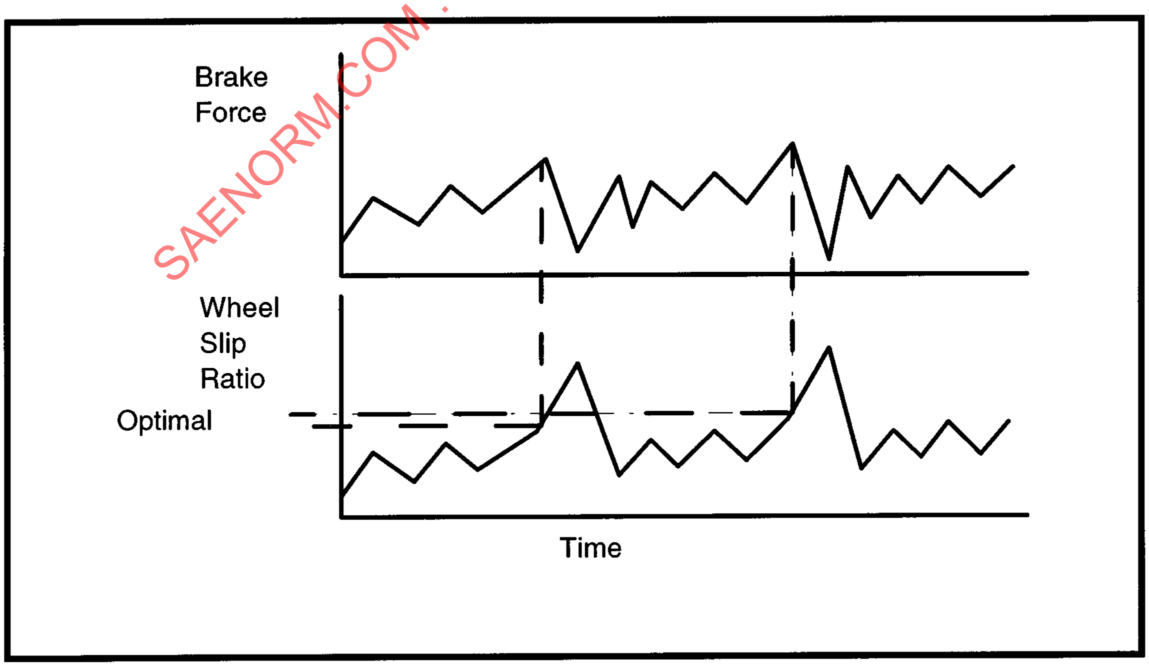


FIGURE 16 - Optimum Slip Ratio Determination