AEROSPACE RECOMMENDED PRACTICE

ARP1070™ REV. E

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Superseding ARP1070D

(R) Design and Testing of Antiskid Brake Control Systems for Total Aircraft Compatibility

RATIONALE

One of the major prerequisites for highly efficient antiskid control is fast braking system response. Earlier versions of the document do have language recommending fast response, but it is not explicit enough or detailed enough. This has become an issue as airframe manufacturers in multiple programs have designed systems with inadequate response for good, much less excellent, antiskid control. There is a need to move consideration of braking system response into the earliest stages of airplane development programs to avoid finding out that response is slow after designs have been frozen and hardware has been produced. In general, there is a need to include desired antiskid performance in all aspects of aircraft design, but this revision will focus primarily on braking system response.

ARP1070E has been reaffirmed to comply with the SAE Five-Year Review policy.

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1. SCOPE

This document outlines the development process and makes recommendations for total antiskid/aircraft systems compatibility. These recommendations encompass all aircraft systems that may affect antiskid brake control and performance. It focuses on recommended practices specific to antiskid and its integration with the aircraft, as opposed to more generic practices recommended for all aircraft systems and components. It defers to the documents listed in Section 2 for generic aerospace best practices and requirements. The documents listed below are the major drivers in antiskid/aircraft integration:

1. ARP4754
2. ARP4761
3. RTCA DO-178
4. RTCA DO-254
5. RTCA DO-160
6. ARP490
7. ARP1383
8. ARP1598

In addition, it covers design and operational goals, general theory, and functions, which should be considered by the aircraft brake system engineer to attain the most effective skid control performance, as well as methods of determining and evaluating antiskid system performance.

For definitions of terms used herein, see Section 7.

1.1 Purpose

To recommend minimum antiskid brake control design practices, laboratory and aircraft test requirements to provide total aircraft system compatibility.

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 International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR1739	Information on Antiskid Systems
ARP490	Electrohydraulic Servovalves
ARP598	Aerospace Microscopic Sizing and Counting of Particulate Contamination for Fluid Power Systems
ARP4754	Guidelines for Development of Civil Aircraft and Systems
ARP4761	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment

ARP4955	Recommended Practice for Measurement of Static and Dynamic Characteristic Properties of Aircraft Tires
ARP1598	Landing Gear System Development Plan
AS8775	Hydraulic System Components, Aircraft and Missiles, General Specification for
AS22759	Wire, Electrical, Fluoropolymer-Insulated, Copper or Copper Alloy

2.2 U.S. Government Publications

Copies of these documents are available online at https://quicksearch.dla.mil.

MIL-B-8075	Brake Control Systems, Antiskid, Aircraft Wheels, General Specification For
MIL-DTL-26500	Connectors
MIL-HDBK-217	Reliability Prediction of Electronic Equipment
MIL-HDBK-454	General Guidelines for Electronic Equipment
MIL-HDBK-5400	Electronic Equipment, Airborne, General Guidelines For
MIL-P-8564	Pneumatic Components (Inactive)
MIL-PRF-81322	Lubrication
MIL-STD-130	Equipment Identification (Active)
MIL-STD-461	Electromagnetic Interference Characteristics, Requirements for (Active)
MIL-STD-704	Electrical Power, Aircraft Characteristics (Active)
MIL-STD-810	Environmental Test Methods (Active)
MIL-STD-882	Safety Requirements (Active)
MIL-STD-1568	Materials and Processes for Corrosion Prevention and Control in Aerospace Weapons Systems
MIL-W-5088	Aircraft Wiring (Inactive - refer to AS50881)

NOTE: DOD cancelled or inactive documents may be applied by the contractor.

2.3 NASA Publications

NASA Technical Services, NASA STI Program STI Support Services, Mail Stop 148, NASA Langley Research Center, Hampton, VA 23681-2199, 757-864-9658, Fax: 757-864-6500, http://ntrs.nasa.gov/.

NASA TN D-1376	Influence of Tire Tread Pattern and Runway Surface Condition on Braking Friction and Rolling Resistance of a Modern Aircraft Tire

2.4 FAR Publications

Available from Federal Aviation Regulations, https://www.faa.gov. Equivalent EASA CS specifications exist and are available at http://easa.europa.eu/document-library/certification-specifications.

AC121.195(d)-1A	Operational Landing Distances for Wet Runways; Transport Category Airplanes
AC25-7	Flight Test Guide for Certification of Transport Category Airplanes
AC23-8	Flight Test Guide for Certification of Part 23 Airplanes
AC20-152	Design Assurance Guidance for Airborne Electronic Hardware
14 CFR 25.109	Accelerate - Stop Distance
14 CFR 25.735	Brakes and Braking Systems
14 CFR 25.1301	Function and Installation
14 CFR 25.1307	Miscellaneous Equipment
14 CFR 25.1309	Equipment, Systems and Installations
14 CFR 25.1316	System Lightning Protection
14 CFR 25.1322	Warning Caution, and Advisory Lights
14 CFR 25.1435	Hydraulic Systems

2.5 Other Publications

NLR-TP-2001-242	Hydroplaning of Modern Aircraft Tires, National Aerospace Laboratory, NLR

2.6 ARINC Publications

Available from ARINC, 2551 Riva Road, Annapolis, MD 21401-7435, Tel: 410-266-4000, www.arinc.com.

ARINC429	Mark 33 Digital Information Transfer System (DITS)
ARINC600	Air Transport Avionics Equipment Interface
ARINC604-1	Guidance for Design and Use of Built-in Test Equipment
ARINC629	Multi-Transmitter Data Bus

2.7 NAS Publications

Available from Aerospace Industries Association, 1000 Wilson Boulevard, Suite 1700, Arlington, VA 22209-3928, Tel: 703-358-1000, www.aia-aerospace.org.

NAS1638	Cleanliness Requirements of Parts Used in Hydraulic Systems

2.8 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

DO-160	Environmental Conditions and Test Procedures of Airborne Equipment
DO-178	Software Considerations in Airborne Systems and Equipment Certification
DO-248	Second Annual Report for Clarification of DO-178B
DO-254	Design Assurance Guidance for Airborne Electronic Hardware

2.9 IEEE Publications

Available from IEEE Operations Center, 445 and 501 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org.

IEEE/EIA 12207.0	Standard for Information Technology - Software Life Cycle Processes
IEEE/EIA 12207.1	Guide for Information Technology - Software Life Cycle Processes - Life Cycle Data
IEEE/EIA 12207.2	Guide for Information Technology - Software Life Cycle Processes - Implementation Considerations

3. ANTISKID, DESCRIPTION OF OPERATION

The antiskid system as used in this recommended practice is the group of interconnected components which interact to prevent inadvertent tire skidding and contribute to shorter aircraft stopping distances by controlling excessive brake pressure, including, but not limited to, wheel speed sensors, control valve(s), and control unit.

The wheel braking system refers to all elements associated with the antiskid system, which coupled together provide deceleration of the aircraft due to wheel brakes. The elements include, but are not limited to, antiskid control components and associated hydraulic installation, electrical system interfaces, wheel(s), tire(s), and brake(s).

The core function of antiskid control is stopping the aircraft as quickly as possible while maintaining directional control and staying on the runway.

The antiskid system provides a means of detecting an incipient skid condition of the aircraft tires and functions to control the brakes so as to maximize braking efficiency, minimize tire damage, and prevent loss of aircraft control. In operation, it modulates the brake clamping force at all times to generate brake torque such that the tire runway friction force is maintained close to its peak value, and thus gives the aircraft maximum available deceleration which results in the shortest possible stopping distance.

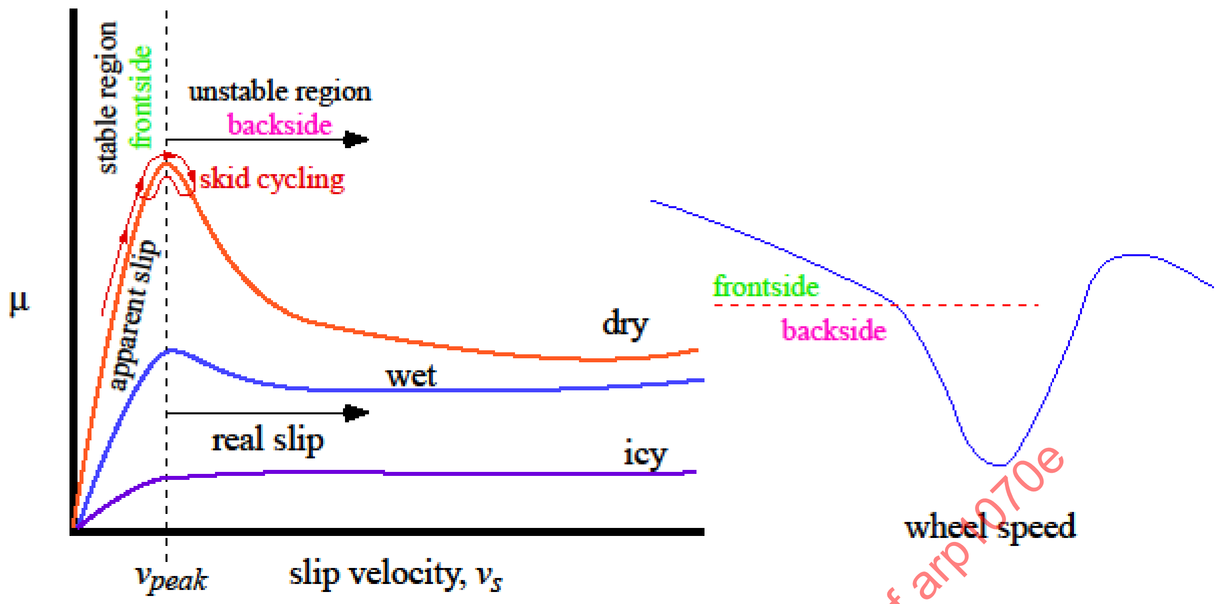

Figure 1 - Mu versus slip curve

Figure 1 shows typical mu-slip curves. The instantaneous tire-runway friction (mu or μ) is a function of wheel slip, which is the difference between the forward speed of the axle and the rotational speed of the wheel multiplied by the rolling radius of the tire. The shape of the mu-slip curve and the location of the peak changes as the aircraft slows down, as well as with runway condition, but there is always a peak. It is this peak that antiskid needs to find to maintain optimal stopping performance.

Slip on the frontside of the mu-slip curve is apparent. Tire stretching and twist about the axle cause the wheel to turn at less than synchronous speed, even though the tire is not actually slipping on the runway. For further explanation, please refer to AIR1739.

The performance of the antiskid system is dependent upon the degree of compatibility achieved between the skid control equipment, the airplane's landing gear (including wheels, tires, and brakes) and airframe, and the remainder of the brake control system.

In operation, the pilot commands pressure or clamping force to the brakes in proportion to the pilot's brake pedal force and/or pedal travel. If there are no incipient skids, the antiskid system does not interfere with the pilot input. If there are incipient skids, the antiskid system overrides the pilot's input and commands a reduction in the brake clamping force to stop the incipient skids. It does this in a manner which seeks to continuously use the available tire-runway friction braking force and minimize wheel skids. In unmanned aircraft, or in the case of autobraking, an onboard computer commands pressure or clamping force directly.

The antiskid system controls the brake clamping force through a brake actuator (a skid control valve, an Electric Motor Actuation Controller (EMAC), or some other means) in response to information obtained from the wheel speed sensor (transducer). The wheel speed information is processed by an electronic controller which then sends a signal to the brake actuator to modulate the brake clamping force. Upon command from the controller, the skid control reduces brake clamping force. When the wheel spins up, the controller reapplies brake clamping force at a controlled rate through the brake actuator until another incipient skid occurs or commanded clamping force is achieved. Several types of brake control-antiskid system types are shown in Figure 2. Note that an alternative to the "brake by cable configuration" is a "brake by master cylinder" configuration.

Note that many existing systems still use analog antiskid controllers, rather than digital computers with embedded processors.

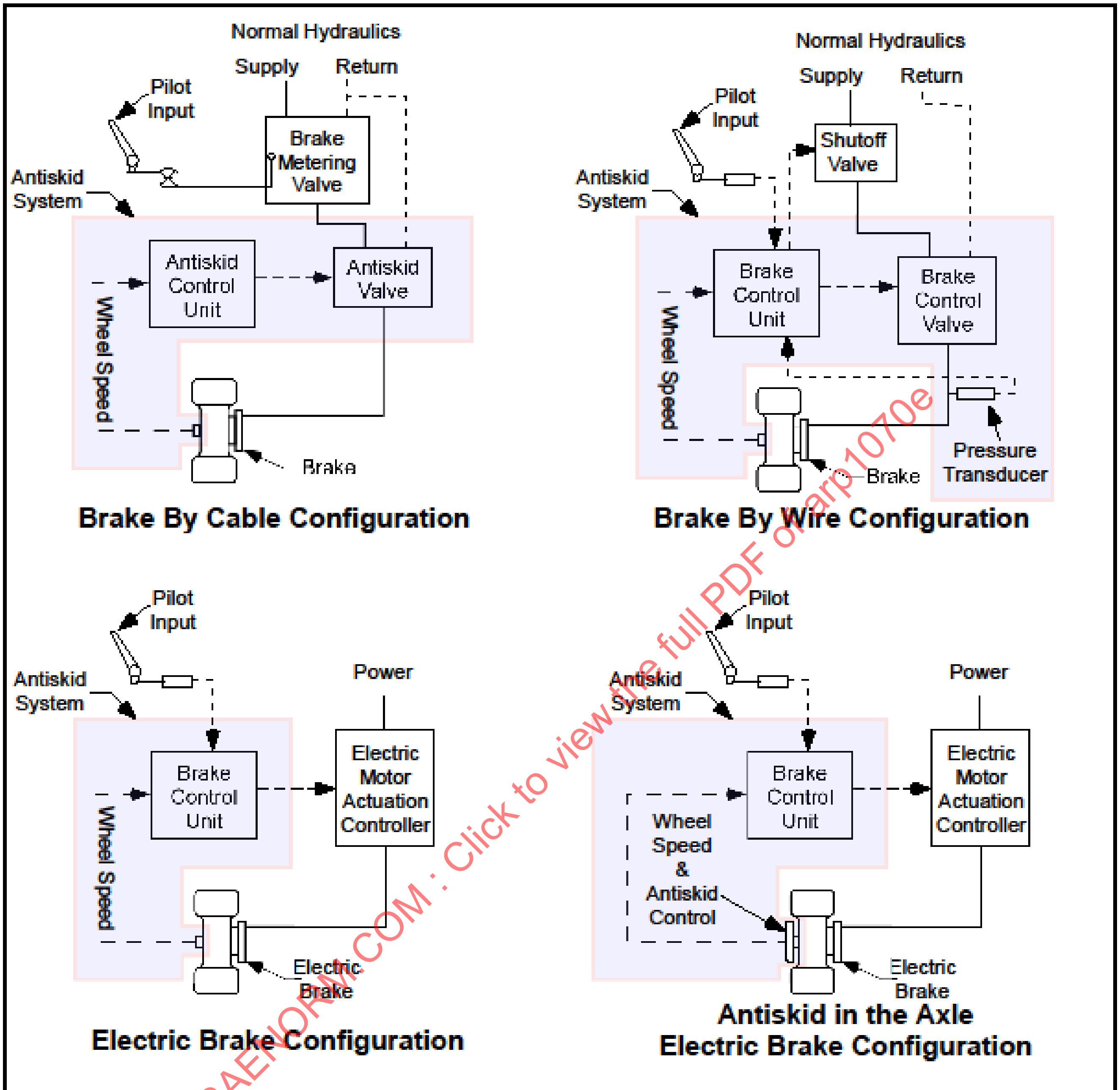

Figure 2 - Antiskid system schematic

4. ANTISKID SYSTEM DEVELOPMENT PROCESS

ARP4754 should be followed. Figure 3 shows the general development process for antiskid systems.

Test equipment and fixtures should be developed to perform the validation and verification activities required by ARP4754.

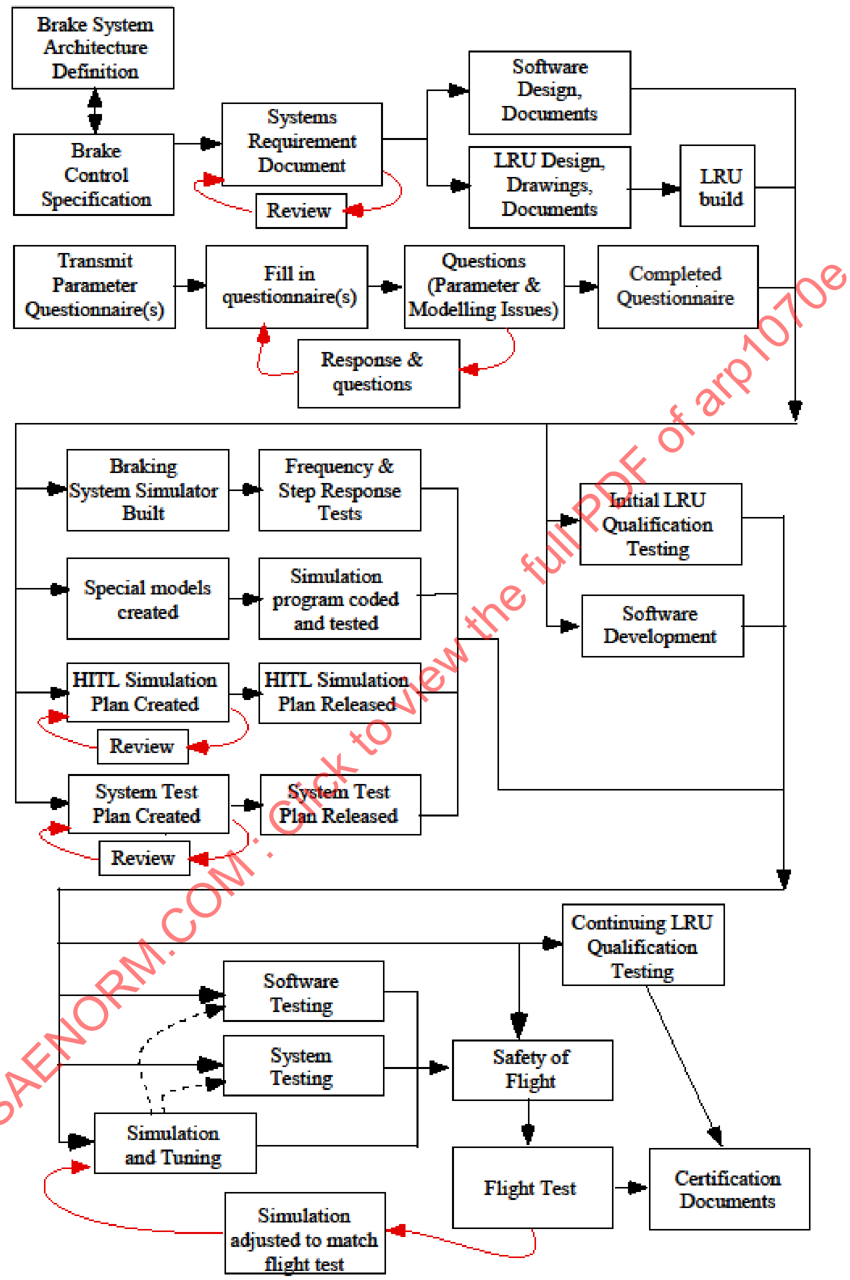

Figure 3 - Antiskid development and testing flowchart

LRU: Line-Replaceable Unit.
HITL: Hardware-in-the-Loop Simulation. Real-time.

4.1 Configuration Consideration

The selection of an antiskid system configuration (architecture) is conditioned by considerations usually including the following:

a. Number and arrangement of braked wheels.

b. Degree of emphasis on stopping/cornering performance.

   1. Individual wheel control refers to the feature where each braked wheel is controlled individually, as a function of its wheel speed. For this function each braked wheel requires its own wheel speed transducer, servo valve, and control circuit.

   2 The antiskid system may be configured to control brake pressure to two or more braked wheels requiring skid control. Pairing or grouping of wheels is a function of landing gear arrangement, performance required, and aircraft directional stability required and should be defined in the procurement specification.

   3 The ability to achieve high antiskid stopping efficiency is dependent on braking system hydraulic response (or electro-mechanical response for electric brake systems). Fast response is necessary for highly efficient antiskid control.

c. Available space.

d. Airplane electrical wiring configuration.

e. Wheel brake friction variation.

f. System cost.

g. Reliability and maintainability.

h. Weight.

i. Failure modes/redundancy.

4.2 Antiskid System Operating Environment

The antiskid system operating environment is the environment in which the antiskid performs its intended function. The environment contains numerous factors with influence antiskid performance, including the wheel braking system, the airframe elastic structure (including struts), the wheel dynamic loading, tire elastic properties, runway friction levels available, runway roughness, ambient and hydraulic fluid temperature, and external influences including EMI, fluid susceptibility, etc.

4.3 Aircraft Braking Environment

The aircraft braking environment is that environment the aircraft experiences during the landing and braking phase of operations, including runway length/width/surface texture/slope/crown/contamination level, wind conditions, temperature/pressure/altitude, touchdown velocity and alignment, and touchdown point proficiency.

4.4 Recommended Data Exchange

Technical data required for design and analysis should be defined in specification or formally agreed to in technical data exchanges to assure the least amount of system deficiencies prior to aircraft test. Example data exchanges are shown in Tables 2 and 3. Table 2 is an example of data supplied by the airframe manufacturer, airframe user, or the brake control supplier/integrator. The higher the fidelity of the antiskid simulation models used in the development process, the more data will be required. Table 3 identifies data and information supplied by the skid control manufacturer.

Table 1 - Airframe manufacturer supplied data (typical, but not limited to)

	Parameter
Aircraft (General)	Aircraft weight - Maximum takeoff, design landing, minimum landing weight, weight empty. Aircraft velocity at brake application - Maximum takeoff gross weight rejected takeoff, overload stop, normal landing weight, minimum flying weight. Geometric parameters - Distance from ground to C.G. (maximum takeoff gross weight, normal landing weight, minimum flying weight), distance from nose gear to main gear, distance from nose gear to C.G. distance between main gear, distance from center of axle centerline to center of gear, distance from ground to C.G. with extended main gear. Aerodynamic parameters - Aerodynamic drag coefficient (takeoff and landing), aerodynamic lift coefficient (takeoff and landing), x, y, z locations for aerodynamic lift and drag, engine idle thrust, engine decay characteristics, and reverse thrust. Miscellaneous - Mass moment of inertia about C.G. (maximum takeoff gross weight, normal landing weight, minimum flying weight).
Landing Gear Shock Strut	Number of wheels per nose and main gear, vertical spring rate (nose and main gear), vertical damping rate (nose and main gear), main gear lateral and longitudinal stiffness, main gear fore-aft natural frequency, main gear fore-aft damping ratio (percent of critical), main gear torsional stiffness.
Brake Hydraulic System	Hydraulic lines - Line length size and type of supply line, brake line, and return line, location and size of restrictors, location of brake metering valve, antiskid control valve. Brake metering valves - Pressure and flow characteristics. Hydraulic supply - Maximum pressure available and flow characteristics. Hydraulic supply and return pressure. Predicted frequency and step response of the brake hydraulic system as a whole (which may involve iterative interaction, analysis, and simulation with the participation of the antiskid, brake, and other LRU suppliers).
Electric Power System	If brakes are electrically actuated, electric wire location and size, means of selecting normal or reserve power to the brake system, and voltage(s) and power available. Predicted frequency and step response of the brake system.
Brake Component	Lining contact pressure (psi), pressure volume characteristics, torque-pressure characteristics including range of friction coefficients (hot brake, cold brake, worn brakes, new brakes), torque-speed characteristics, weight of brake, moment of inertia of brake rotors. Number of stators and rotors. Number of pistons and piston area.
Wheel/Tire Parameters	Tire size and type, fore-aft spring rate, vertical spring rate, weight, normal tire pressure and rolling radius, wheel weight, tire peak ground coefficient versus velocity on normal dry runway, moment of inertia of tire and wheel.
Miscellaneous	Skid control components - Schematic, envelope, and mounting requirements. Interface requirements for controller, control valves and wheel speed sensors. System fault isolation and indication requirements.
	Speed requirements - Maximum and minimum operational speeds.
	Skid control efficiency requirements -
	Special skid control features required - Touchdown protection, locked wheel protection, paired wheel control, auto-braking, warning devices for pilot, on-off switch, parking brake, etc.
	Operational environment for components -

Table 2 - Antiskid manufacturer supplied data

Antiskid Manufacturer Supplied Data
• Electronic schematics. • Interface control documents (ICDs). • Operational considerations. • Failure modes and effects analysis. • Requirements verification compliance matrix - Confirmation of requirements compliance, and how to be verified (inspection, demonstration, analysis test). • Skid control component characteristics - as required by customer for overall brake system analysis. Includes weight, C.G, envelope, input/output characteristics, interface characteristics, control algorithms description. • Maintainability - Recommended system maintenance and checkout procedures, required ground support equipment. • Reliability predictions. • Test procedures/reports - Acceptance test, flight justification test, and qualification test. • Complete working drawings including proprietary data appropriately marked. • System safety evaluation in accordance with ARP4761. • Simulation test results. • Data demonstrating compliance with DO-178 (clarification in DO-248). • Data demonstrating compliance with DO-254. • Data demonstrating compliance with ARP4754.

5. AIRCRAFT SYSTEMS AND AIRCRAFT OPERATIONAL GOALS, EFFECT ON ANTISKID

5.1 Antiskid Interactions with the Aircraft, Stopping Performance

Figure 4 shows some of the important interactions between antiskid core function, aircraft systems, and aircraft operational goals.

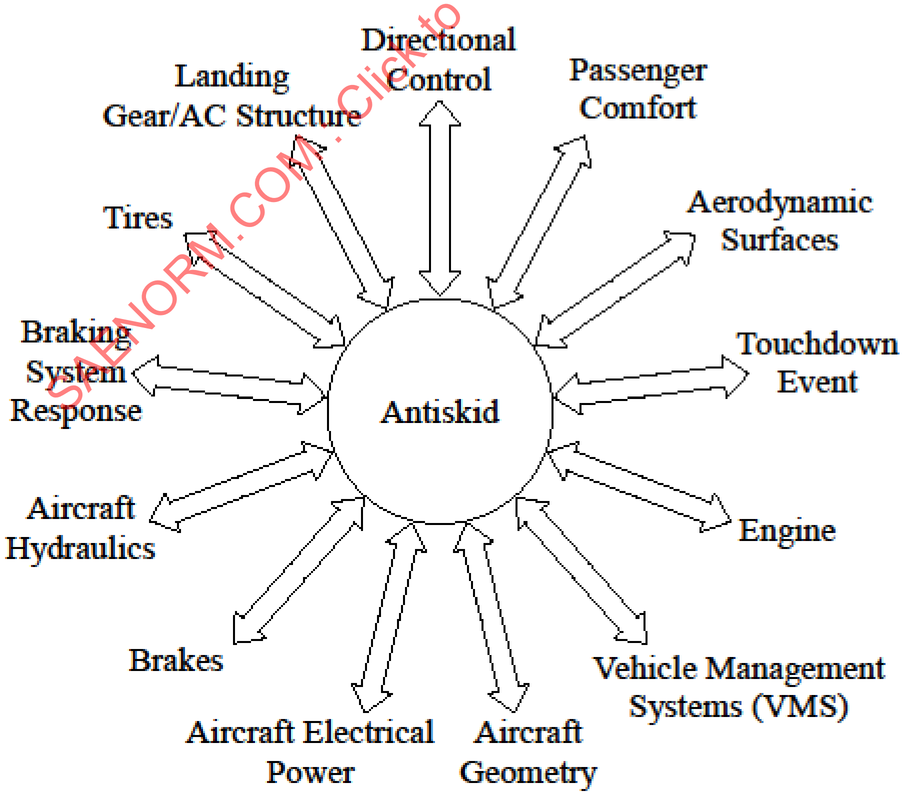

Figure 4 - Antiskid aircraft interactions

5.1.1 Braking System Response

Fast brake response is a prerequisite for highly efficient antiskid control. Fast response also improves the robustness of the control and its ability to adapt to future changes to the aircraft. Both large and small signal response should be considered. (Note that other aircraft systems may also affect the maximum achievable antiskid efficiency.)

Note that, when necessary, it is always possible for brake control to slow down response in consideration of other aircraft requirements, such as pressure ramp-up (and its associated loads), as well as aquaplane logic.

The airframe manufacturer is responsible for bringing all of the relevant parties together to ensure that all analysis and testing is performed to achieve the response necessary for the required level of antiskid performance. For system upgrades not involving the airframe manufacturer, a systems integrator may take on that role.

As a starting point, the following level of response should be targeted. In-depth analysis of the system may modify these numbers.

Step response (large signal):

- Brake release from maximum command to zero torque:
    - Should be 40 ms or less for maximum antiskid efficiency (typically 90% or higher).
    - Should be 80 ms or less for reasonable antiskid efficiency (typically 85% or higher).
    - See the definition of brake release time in Figure 9.
    - Note that the “maximum command” is generally system pressure for hydraulic brakes or the maximum force that can be applied to the brake pistons for an electric brake. If the brake torque gain is high enough so that the skid level is always significantly lower than the maximum command, maximum skid level (generally seen during maximum rejected take off or overload landings) may be substituted for maximum command.

Frequency response (small signal):

- 90 degree crossing point of the phase shift in a frequency sweep:
    - Should be 12 Hz or higher for maximum antiskid efficiency.
    - Should be 8 Hz or higher for reasonable antiskid efficiency.

5.1.2 Aerodynamic Surfaces

For optimal stopping capability, it is recommended that the aerodynamic surfaces generate as much drag as possible while directing the greatest possible load onto the main wheels while maintaining enough load on the nose wheels for effective steering.

At high speeds, rudder control may reduce or eliminate the need for differential braking to maintain directional control.

5.1.3 Engine Thrust

The effect of engine thrust on stopping performance should be considered.

The effect of reverse thrust should be considered.

The effects of feathering propeller driven airplanes should be considered. The effect of propellers on aerodynamic surfaces should also be considered.

5.1.4 The Touchdown Event

The touchdown event affects stopping distance, as well as the time it takes for antiskid to reach the peak of the mu-slip curve.

After a hard landing, if the aircraft bounces and significantly lowers the weight on the wheels, the task of antiskid initializing itself to find the skid level may be much more difficult.

Note that a touchdown protection feature should be included to prevent brake application before touchdown and wheel spin up.

5.1.5 Vehicle Management Systems (VMS)

Vehicle Management Systems (VMS) may perform functions that might traditionally be performed in the antiskid controller, as well as additional functions that may affect antiskid performance and control. These functions might include (but not be limited to):

- Touchdown protection.
- Delay of brake application until such application will not cause adverse aircraft structural issues. (Example: Delay until all landing gears are on the ground.)
- Limitation of brake torque magnitude or rate of application to prevent aircraft structural damage.
- Directional control.

Specification of antiskid performance requirements should take VMS limitations of brake application into account.

Conversely, the design of VMS software related to braking should take antiskid into account.

Interfaces between the VMS and the antiskid controller should be designed to have enough bandwidth and speed (including margin for potential expansion) to meet all of the control interaction requirements.

5.1.6 Aircraft Geometry

It is recommended that stopping capability and steering capability be considered when laying out the geometry of the main landing gears, nose landing gear, and range of center of gravity location.

A center of gravity too far forward of the main gears, in relationship to the wheelbase (distance between the nose and main gears) will increase the weight on the nose as compared to the main gears. As the aftward directed braking force is the product of the weight on the main wheels and the tire runway coefficient of friction, the lower the proportion of weight on the main wheels, the longer the stopping distance.

Braking itself produces a nose down pitching moment on the aircraft. The higher the center of gravity, the more weight will be transferred to the nose during braking.

A short wheelbase and wide track (lateral distance between the main gears) will increase the yaw moment produced on the aircraft when antiskid releases pressure on one side of the airplane but not the other, thus causing the aircraft to veer to the left or right. Methods insuring that antiskid releases pressure on both sides simultaneously can alleviate this problem but they may increase the stopping distance.

5.1.7 Aircraft Electrical Power System

The antiskid/brake control equipment should be compatible with the aircraft power quality environment.

For electric brake systems, the electrical power system should have sufficient voltage and current capability to meet the needs of the brake system. Reserve electrical power should also be available if the primary electrical power system fails.

5.1.8 Brakes

5.1.8.1 Brake Response

Brake system response is a shared responsibility between the airframe manufacturer (or system integrator for certain aircraft upgrade programs), the antiskid manufacturer, and the brake manufacturer. The airframe manufacturer should manage the roles and responsibilities of these three players to ensure that the system as a whole is responsive enough for highly efficient antiskid control.

Fast brake response, as measured by both step and frequency response, is a prerequisite for highly efficient antiskid control. Note that the response of the entire braking system must be considered; thus, the brake itself must be fast enough for that response to be achievable. See 5.1.1.

Airframe manufacturer requirements for brake reponse should be included in the brake procurement specification.

Brake fill time, or the time from the initial command to the brake and piston contact, should be minimized.

Brake release time should be as fast as possible. If a wheel locks up or goes into a very deep skid, antiskid must be able to reduce torque quickly to allow it to spin up again. When antiskid commands zero brake torque, the response of the brake system must be as fast as possible.

At a system and brake level, response speed at low command levels for hydraulic brakes may be increased by the concept of zero torque pressure (ZTP), whereby the brake is released enough for the wheel to be unbraked, but the pressure does not drop to zero. As brake torque is not usually measured, care must be taken to ensure that the ZTP command is set low enough to reliably result in zero torque and not a small amount of torque which would lead to a dragging brake.

Note that the response of the system will be tested as a whole, using a rig that duplicates the aircraft braking hydraulic system or the electric brake system (see 8.1).

5.1.8.1.1 Fluid Displacement, Hydraulic Brake

Hydraulic fluid volume change from return pressure to initial brake contact pressure should be minimized to reduce the amount of flow required to quickly fill the brake. In combination with long brake lines, high flow rates can result in water hammer when the pistons contact the brake stack.

Hydraulic fluid volume change should be a minimum from initial brake contact pressure to maximum operating pressure for both new and fully worn brake conditions (compatibility with the antiskid system should be confirmed). A relatively high brake structural spring rate and self-adjusters should be considered to accomplish the above. A brake stiffness curve should be defined in the procurement specification. This part of the displacement curve is particularly important for determining the flow that must be driven through the system during antiskid modulation, including brake releases. The higher the slope of pressure versus volume, the better.

Figure 5 shows how brake fluid displacement can be better or worse for antiskid hydraulic system response, depending upon the brake design and brake wear level.

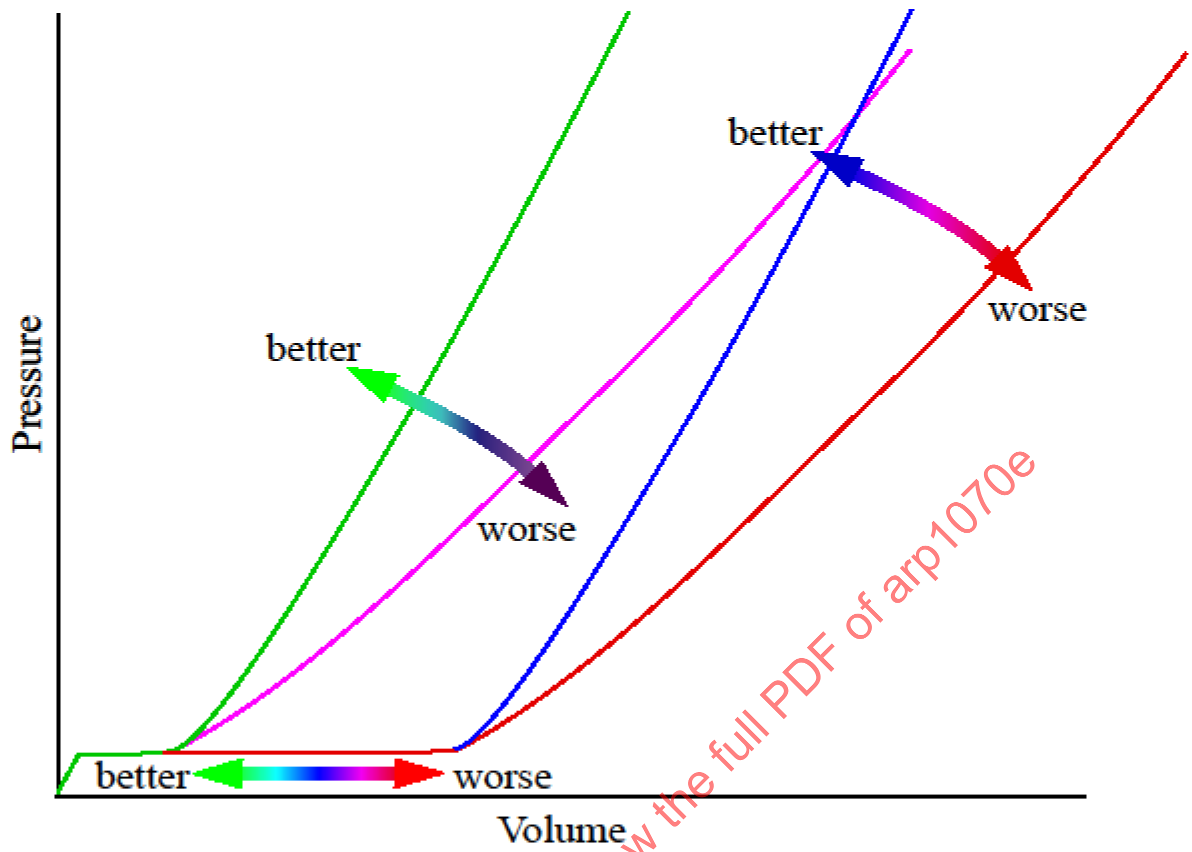

Figure 5 - Brake displacement, pressure versus volume

5.1.8.1.2 Fluid Passages, Hydraulic Brake

Ports and internal fluid passages should be designed to assure minimum air entrapment and minimum flow restrictions. However, this should be balanced with the need to include brake passage restrictions to provide additional damping to minimize brake vibrations. For example, damping for the brake whirl modes of vibration is frequently achieved by brake passage restrictions. Flow restrictions should not be so severe that, during a brake fill, an upstream piston contacts the brake stack noticeably before pistons further downstream. Small diameter restrictions can significantly affect brake hydraulic response.

5.1.8.1.3 Communication and Computational Delays, Electric Brake

Communication delays between the antiskid system and the electric brake motor actuator (EMAC) and between the EMAC and the brake actuators should be minimized. This lag is the equivalent of transport delay down a long hydraulic line in a hydraulic brake.

The computation time of the EMAC should be fast enough to maximize the response of the electric brake actuator.

5.1.8.1.4 Electric Brake Actuator

The response of the actuators should be sufficient to allow for highly efficient antiskid control. See 5.1.1.

5.1.8.1.5 Mechanisms, Hydraulic and Electric

Brake release mechanisms, self-adjusters (if employed), brake rotor wheel drive key interface, brake stator torque tube spline interface, and hydraulic seals should be designed to minimize friction and the hysteresis associated with application and release of the brakes. Excessive hysteresis can interfere with antiskid control and its ability to reduce brake torque as required.

5.1.8.2 Brake Vibration

Interactions between antiskid and brake dynamics should be considered. It is also sometimes possible to relieve adverse effects of brake dynamics by changing the antiskid system characteristics.

Brake vibrations that can interfere with the antiskid control should be avoided. These include:

- Vibrations that cause cycling in piston pressure sufficient to interfere with antiskid's modulation of brake pressure.
- Vibrations that occur at some multiple of wheel speed. Steel brakes with the same number of brake pistons as expansion slots in the rotors and the stators are an example of a design that can produce this sort of vibration.
- Vibrations that cause the wheel speed transducer to measure incorrect wheel speed.
- Vibrations that excite landing gear natural frequencies.

5.1.8.3 Brake Friction Properties

A goal of brake design for antiskid systems should be consistent friction characteristics. Antiskid can adapt more easily when the shape of the friction curve and its rough level is similar from stop to stop throughout the life of the brake.

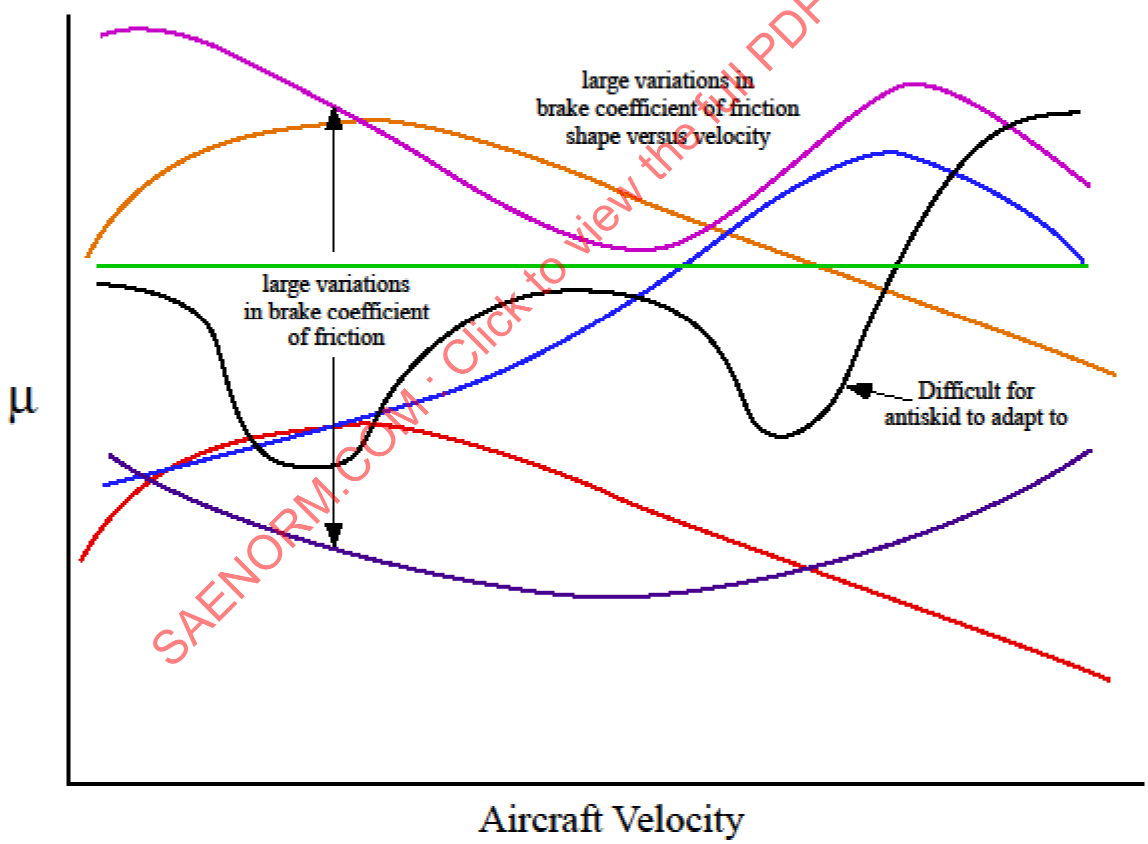

Figure 6 - Brake friction curve variation

Figure 6 shows a variety of brake mu curve shapes. Each of these curves requires antiskid to adapt in quite different ways as the airplane slows down. The flat, green curve is the "ideal." Variations in mu such as those shown in the black line are very difficult for antiskid to adapt to and should be avoided.

If under some conditions brake friction increases throughout a given speed range and, in other conditions, brake friction decreases throughout that same speed range, antiskid has to be tuned for both possibilities. The compromise may result in a reduction in overall stopping performance.

In addition, if the brake coefficient of friction is much higher in some conditions than others, antiskid is less able to use the skid pressure level it has determined through its control action as a surrogate for the tire-runway coefficient of friction.

Antiskid should be designed and tuned to adapt to the full range of curve shapes and brake torque versus pressure gains expected to be seen in service. However, extreme variation in the brake torque curve shapes and brake torque versus pressure (or clamping force) may limit the stopping efficiency achievable by antiskid.

Ideally, brake mu should not be so high that the skid pressure level is extremely close to piston contact pressure during stops on extremely slick runways. Piston contact pressure represents a major discontinuity in pressure response and it is difficult for antiskid to modulate near this discontinuity. (Note that piston contact pressure may also be referred to as brakes tight pressure, zero torque pressure, or the brake knee.)

5.1.8.4 Dynamometer Testing of Brakes

Dynamometer testing of brakes is essential to the evaluation of the skid controls system for the evaluation of total antiskid performance. Test data from landing energy and overload energy stops help determine:

- Brake torque versus pressure or clamping force.
- The effect of temperature and velocity on the values of developed torque.
- Other nonlinear effects that need to be accounted for in the antiskid system tuning.
- Tests that better characterize brake torque hysteresis.

This data should be used in simulator tuning of the antiskid system.

5.1.8.5 Reaction Torque

The brake's torque should be reacted in such a manner that brake applications result in minimal variations of the vertical wheel loads. However, as this may not always be possible, antiskid should be designed and tuned to deal with variations in vertical load, recognizing that extreme variations may limit the stopping efficiency achievable by antiskid.

5.1.8.6 Zero Command

A zero clamping force command should result in the complete removal of clamping force.

5.1.8.7 Post Certification Brake Changes

If changes to the brake must be made after certification, which will result in changes to the brake friction curves or to the hydraulic response of the brake, obtaining consultation by the brake control supplier should be seriously considered.

5.1.9 Aircraft Hydraulics (Hydraulically Actuated Braking System)

The braking system hydraulic components should be designed so that, as a system, they can achieve the brake frequency and step response necessary for antiskid to achieve optimal stopping performance. See 5.1.1.

ARP4752B Section 6 should be consulted for the design of the braking hydraulic system. Section 6.2 should be considered for the initial sizing of hydraulic lines (tubing).

Figure 7 is an example braking hydraulic system. It is intended to show most of the types of hydraulic components that might be found in a braking hydraulic system.

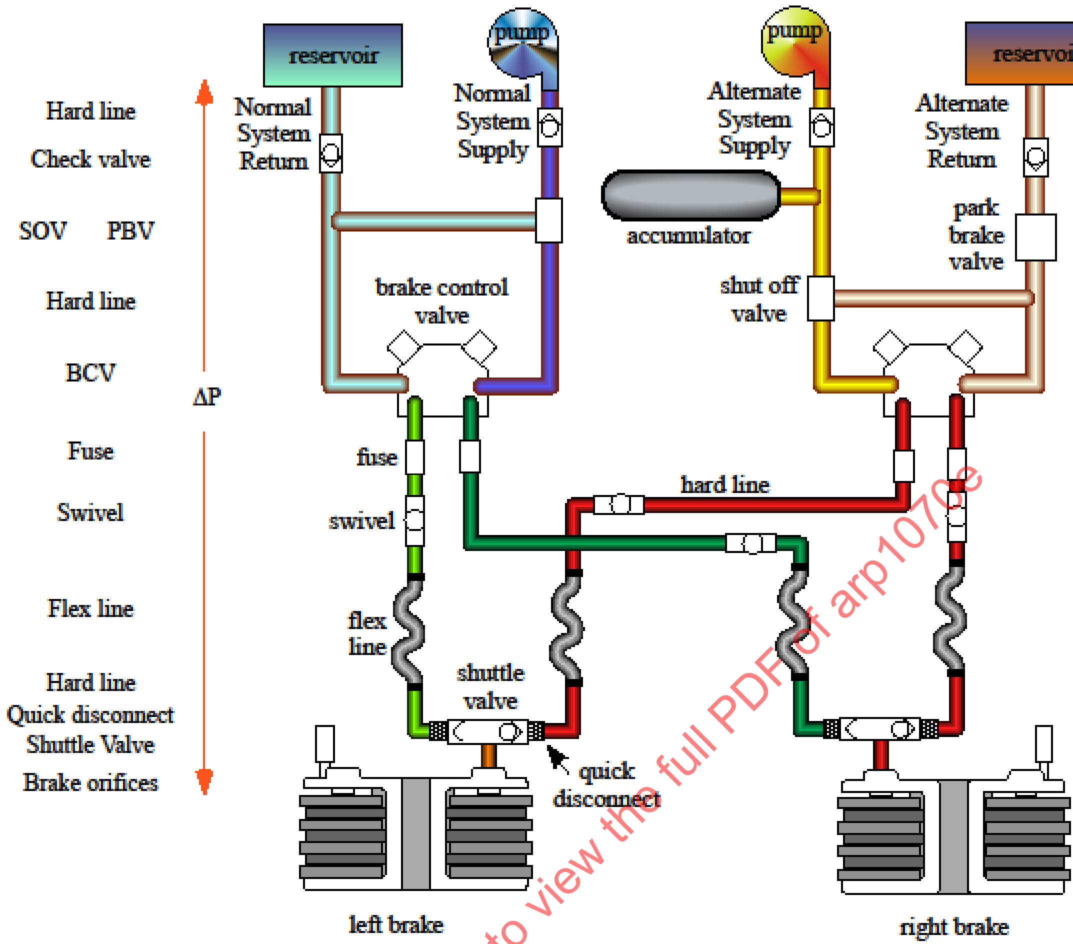

Figure 7 - Hydraulic system example

It is critical to estimate the maximum flow that is required for the level of antiskid performance required and to ensure that all of the components from supply to brake or from brake to return are sized so that the sum of the pressure drops across all of the components does not exceed the total available pressure drop.

Note that the amount of fluid that has to be moved does not depend solely on brake displacement (see 5.1.8.1.1). Typically, the amount of fluid that has to be moved must also include the fluid in the lines between the brake control valve (BCV) and the brake. The supply and return lines should be sized to handle the flow with minimal pressure drop. As a rule of thumb, when two lines merge into one, the flow area of the merged line should roughly double (see Figure 8).

High bulk modulus hydraulic fluid and stiff lines will reduce the amount of fluid that has to be moved as compared with low bulk modulus fluid and less stiff lines (or flex hose).

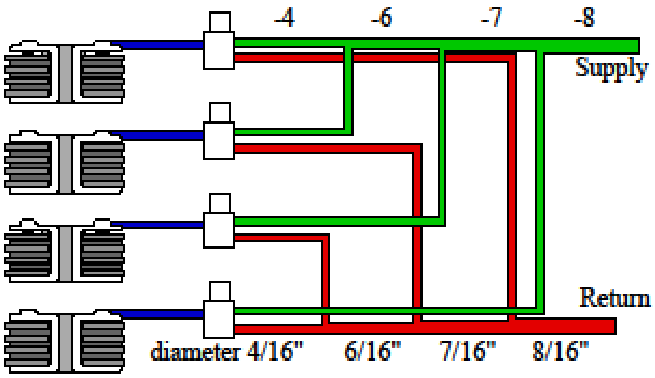

Figure 8 - Merging supply and return lines

Significant restrictions in the supply and return lines should be avoided. If not, and there is a significant volume of fluid in the lines between the restriction and the brake control/antiskid valve, that fluid will also have to be taken into account when determining the magnitude of flow required for antiskid control.

Significant restrictions in supply lines providing pressure to multiple antiskid valves should be avoided, as the drops in pressure during antiskid modulation may cause the valves to "talk" to one another, i.e., the drop in supply pressure during pressure application on one brake will cause pressure to drop on the other brakes using the same supply source. This may reduce antiskid performance.

Before finalizing a braking system architecture and the drawings that implement the details and dimensions of that architecture, it is highly recommended that sophisticated analysis and/or simulation of the response of the system be performed.

The pressure source, whether it comes from shared aircraft system supplies or a pump dedicated to the braking system, should be designed with enough system flow to support antiskid.

Hydraulic lines should be sized so that the total braking hydraulic system can achieve step and frequency response necessary for high stopping performance antiskid control. The length of the lines between the antiskid valve and the brake should be made as short as possible. The effect on total braking system response of flex hoses, swivels, filter fittings, fittings, and valves should be considered.

The inclusion of an accumulator should be considered to reduce supply pressure drop during brake fill, to provide flow during system supply pressure failure both for antiskid modulation and/or a given number of brake applications to meet regulator and/or specification requirements, and to provide parking brake pressure.

The return pressure and return lines should be sized so that the antiskid system is never unable to reduce the brake pressure below the piston contact pressure.

5.1.9.1 Definition of Hydraulic Brake Release Time

During a brake release, the slope of the release will decrease as the brake pressure approaches return pressure. This "tail" is not bad for antiskid. So, to avoid penalizing systems with long tails at low pressures, the method of determining brake release time illustrated in Figure 9 should be used.

Note that the command to the brake control (or antiskid) valve steps from maximum command to zero at the start of the release. Brake pressure is measured at the piston farthest away from the brake inlet port.

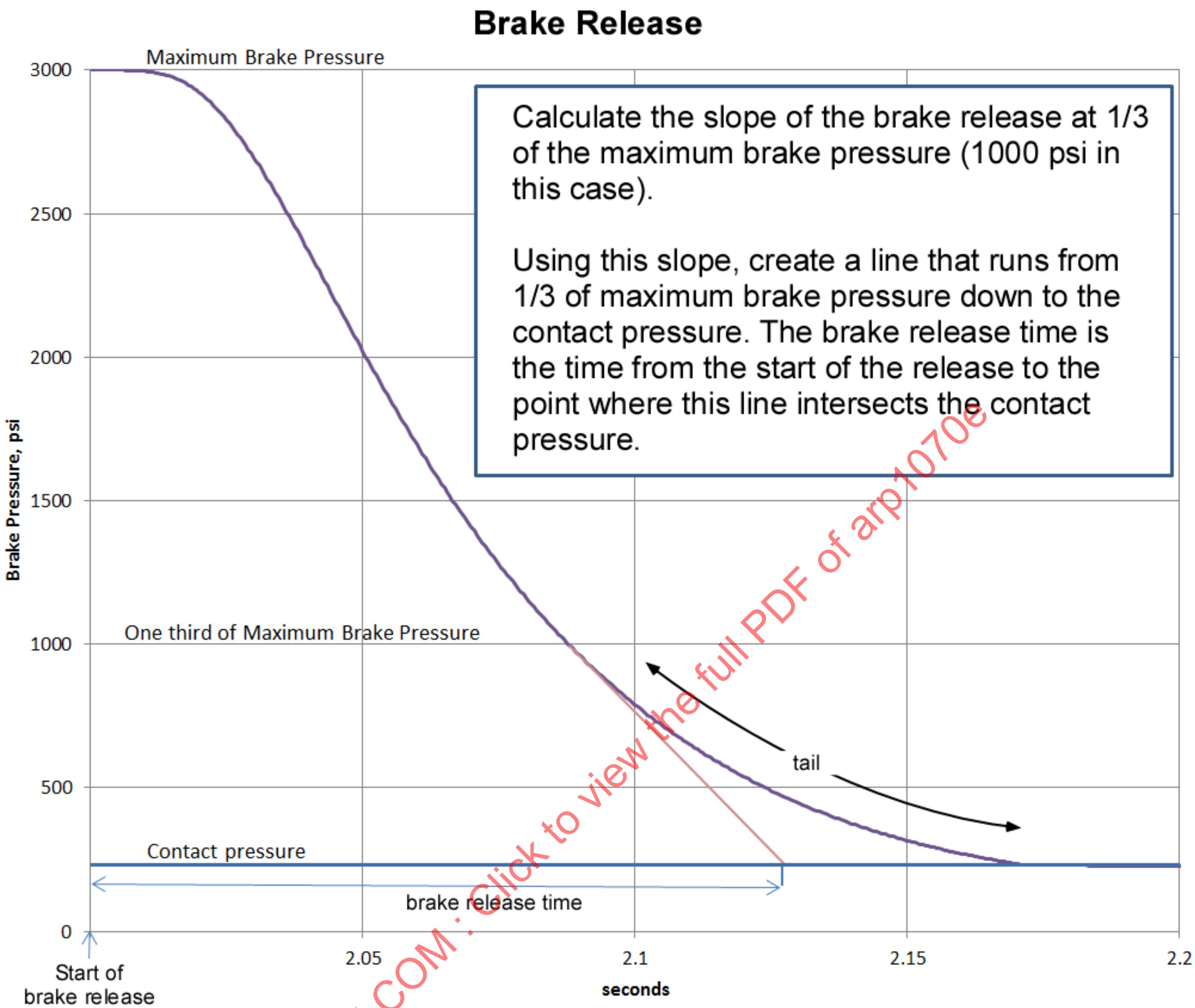

Figure 9 - Brake release time

5.1.10 Tires

The effect of tire selection on the ability of antiskid to provide both directional control and high efficiency stopping should be considered.

The tire runway coefficient of friction goes down as tire pressure goes up by about 0.0011 per psi. However, particularly on contaminated runways, and contaminated wet runways, the coefficient is also very dependent on aircraft velocity and the type of contamination. Refer to NASA TN D-1376, page 24.

The lower the tire aspect ratio, the lower the dynamic hydroplaning speed may be. Refer to NLR-TP-2001-242.

$V_P = 9\sqrt{p}$ Horne's equation for dynamic hydroplaning (Bias ply)

$V_P = 6.4\sqrt{p}$ NLR-TP-2001-242 equation for dynamic hydroplaning (radial-belted)

V_P (kts) dynamic hydroplaning speed

p (psi) tire pressure

The tires may interact with the landing gear to produce shimmy-like motion. This is discussed more thoroughly in 5.1.10.4. Tire footprint area, inflation pressure, type (radial/bias), fore and aft stiffness, lateral stiffness, vertical stiffness, torsional stiffness, relaxation length, mass, inertia, tread design and wear, rolling resistance, diameter, damping characteristics, and friction characteristics all contribute to tire interactions with the landing gear and antiskid system and should be considered when designing or selecting tires.

5.1.11 Landing Gear

The dynamics of the landing gear, and how it will interact with antiskid control, depend up the geometry of the gear, as well as its mass, stiffness, and damping properties. Fore-aft motion is the most important to antiskid control.

Note that the flexibility of the aircraft structure to which the landing gear is attached will significantly affect the mass and stiffness properties of the landing gear. This includes the wing, if the landing gear is wing mounted. When analyzing and modeling landing gear dynamics, the effect of the aircraft structure should be included.

Many types of landing gear arrangements are possible and are in use. Antiskid is only one of many design considerations that go into the selection of a gear configuration. Four of the most common are shown in Figure 10.

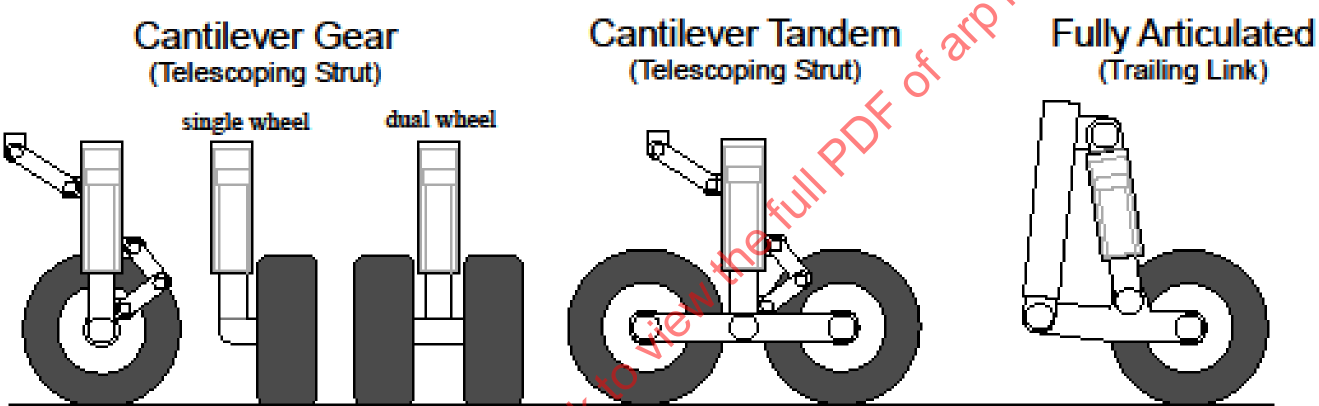

Figure 10 - Typical types of main gear

5.1.11.1 Cantilever Tandem Landing Gear

In this type of landing gear, the truck mass and pitch dynamics are important, as well as truck pitch damping. Techniques to minimize truck pitch oscillations should be incorporated in the design. Some gears of this type include a pitch damping device. Brake torque take out, which may be directly reacted to the truck or to the shock strut above or below the truck pivot point, is important as it affects the pitching moments on the truck during braking. As truck pitch alternately loads and unloads the fore and aft wheels, antiskid is directly affected as it seeks the brake torque level that will provide maximum braking. The loaded radius of the tire, and rolling radius of the tire, are directly affected by truck pitch. The resulting wheels speed oscillations feedback directly into antiskid control. The interactions of the truck and antiskid control should be considered when this type of landing gear is selected.

5.1.11.2 Landing Gear Vertical Suspension

As seen in Figure 11, the nose and main gears provide suspension for the aircraft. A sufficient amount of damping is needed for antiskid to be able to obtain highly efficient stopping performance.

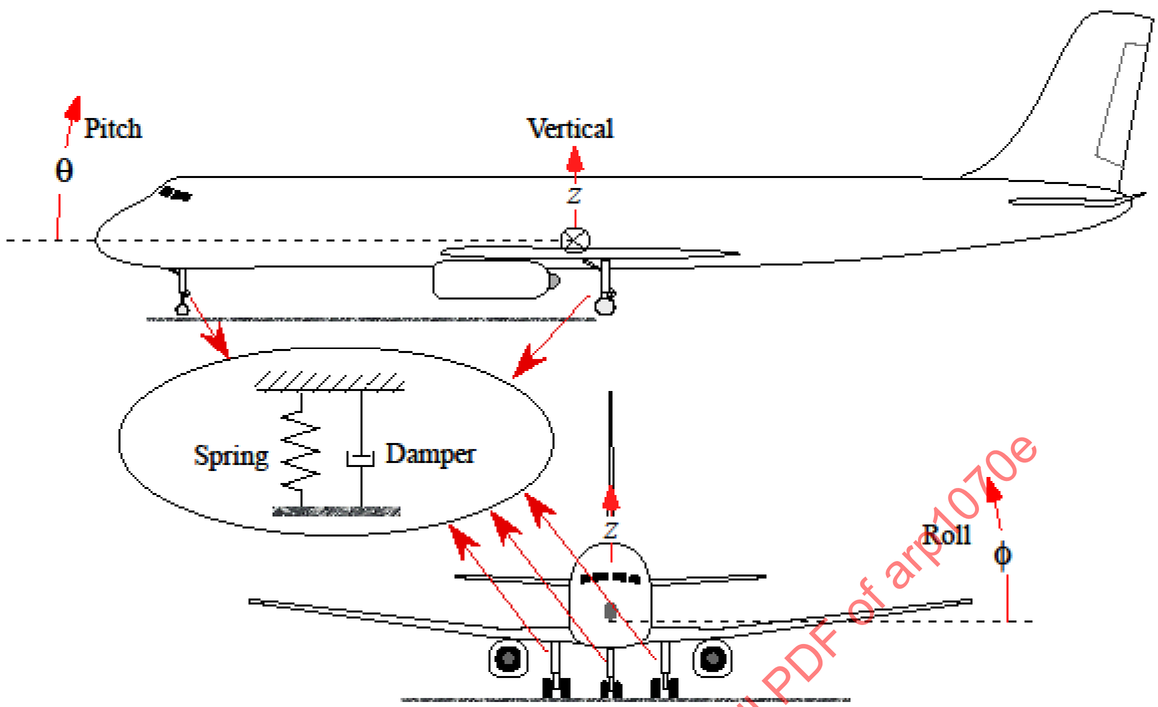

Figure 11 - Suspension

For optimal antiskid stopping performance, the landing gear should be designed to provide adequate suspension, quickly damping out aircraft cyclical vertical, pitch, and roll motion and the resultant variations of the weight on the main wheels. Figure 12 illustrates two examples of how landing gear design choices can result in poor suspension.

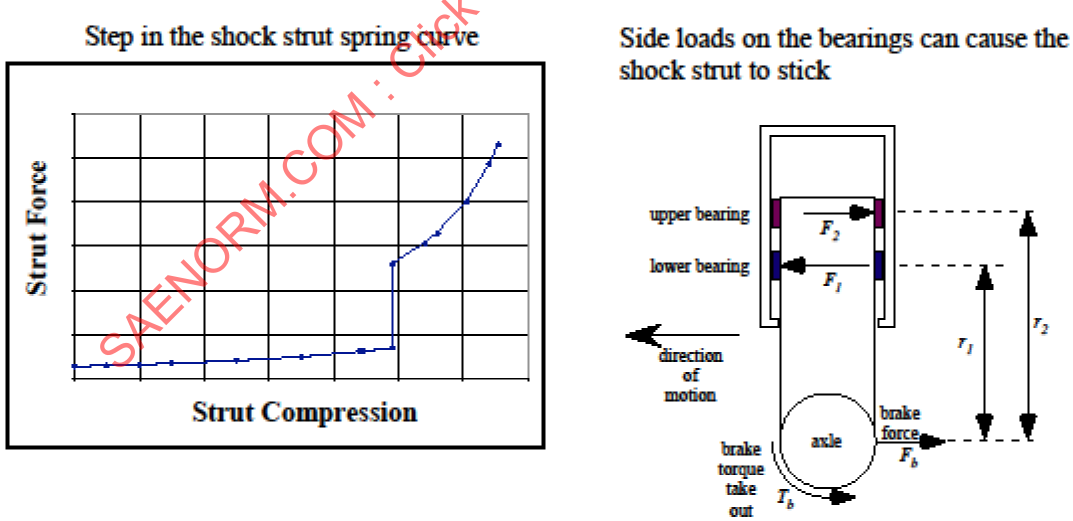

Figure 12 - Shock strut step and stick

Shock struts with steps in the spring curve should be designed so that the on-ground vertical load is never in the range of the step. Operating on the step results in significant vertical load changes on the gear with little or no stroke change. This results in poor antiskid efficiency. Similarly, a shock strut that has excessive sticking due to excessive bearing friction will result in the same problem with vertical load. Sticking generally results from side loads on the bearings. In cantilever gears and some other types of gears, braking forces produce side loads on the bearings. Other landing gear arrangements may generate significant side loads unrelated to braking forces.

Figure 13 illustrates how aircraft vertical, pitch, or roll oscillations can drive skidding. Any of these oscillations will result in oscillation of the weight on the wheel. If the magnitude of this oscillation (W_w) is significant compared to the average weight on the wheel, antiskid may be unable to track the skid level (brake torque required to skid the wheel) without driving the wheel into a deep skid each time that the weight on the wheel drops. Note that the skid level is directly proportional to the weight on the wheel. Also note that changes in the rolling radius driven by changes in tire compression driven by the weight on wheels oscillation can be reflected into the wheel speed measured by antiskid.

Antiskid can, and should, be tuned to avoid driving aircraft pitch oscillation, but if there is little damping in the pitch mode, this may result in loss of stopping efficiency. In the real world, antiskid will always lag the skid level, so when weight on wheel oscillations become large in amplitude, skids will result. Overall (not instantaneous) stopping performance is a compromise between aggressively tracking the skid level and avoiding the excitation of pitch. If the landing gears provide little to no damping, antiskid will have to be tuned more towards avoiding pitch excitation and less towards aggressively seeking the skid level.

And note that the primary input antiskid must use to try to accomplish this is wheel speed.

For these reasons, adequate aircraft suspension is critical for high stopping efficiency antiskid.

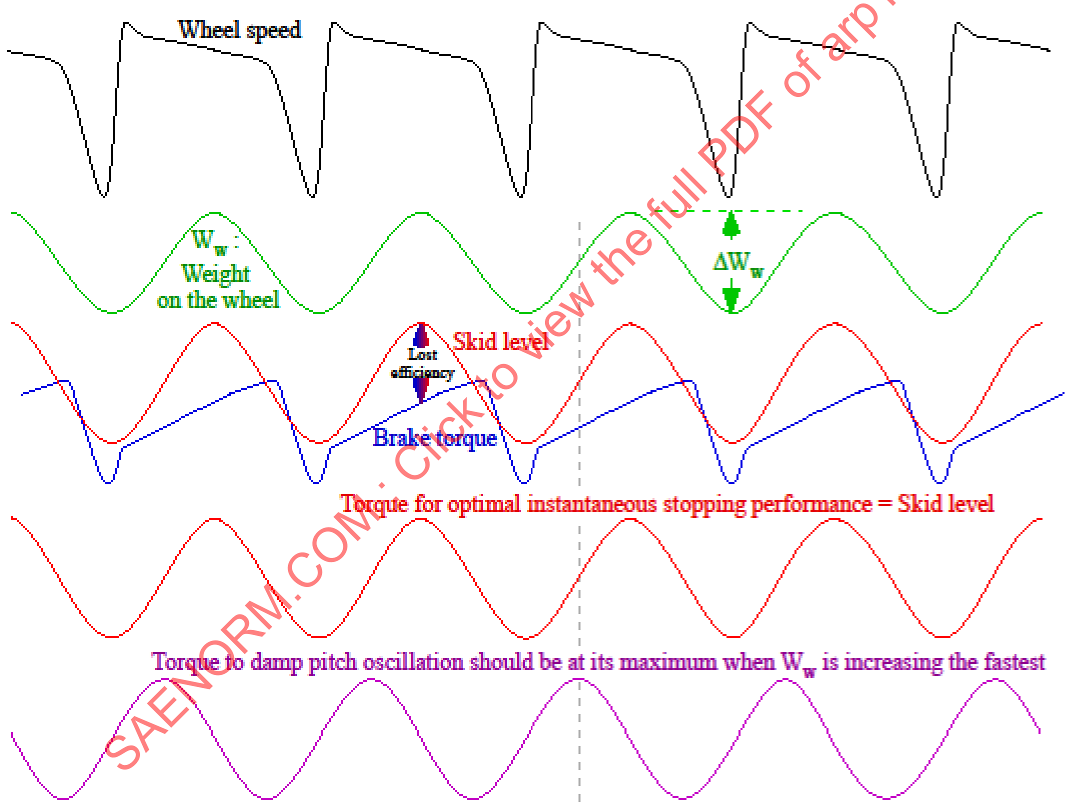

Figure 13 - Aircraft pitch, roll, or vertical oscillation

Further explanation of how locked out main gear suspension can affect antiskid may be found in AIR1739.

5.1.11.3 Forward Raking

For optimal antiskid stopping performance, and maximal fatigue life of the gear drag brace, forward raking of cantilever main landing gears should be avoided.

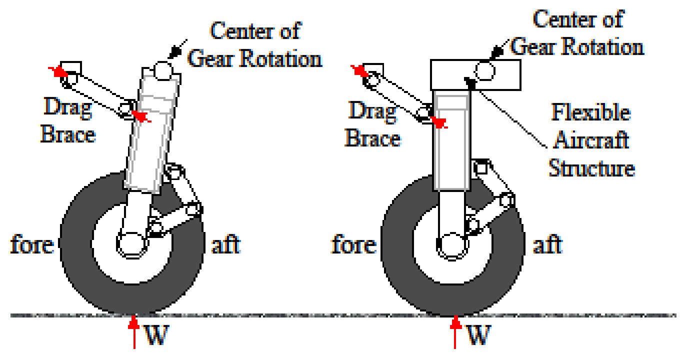

Figure 14 - Forward raked gear

Forward raked gears may be inherently unstable under braking and they may present particular difficulties in achieving highly efficient antiskid control.

Further explanation of how forward raked gears may affect antiskid may be found in AIR1739.

Also, note that, in both cases shown in Figure 14, the drag brace is under compression when there is no braking. This occurs because the vertical load transferred to the axle/wheel by the tire is forward of the center of rotation of the gear. This produces a moment that tends to rotate the gear forward. Reacting this moment puts the drag brace in compression. Braking forces will pull the drag brace into tension. Antiskid modulation may cause reversals in the loading of the drag brace, from tension to compression then back to tension, particularly when the antiskid releases large amounts of pressure due to deep skids. These reversals in loading may reduce the life of the drag brace. Tuning antiskid to limit these reversals may reduce stopping performance.

5.1.11.4 Gear Stability

Requirements for antiskid with respect to gear stability may be found in 6.2.

Main gear shimmy is particularly problematic for antiskid. A main gear with a low shimmy stability margin may be difficult for antiskid to deal with, as the ordinary antiskid modulation necessary for high performance stopping may excite the gear into shimmy.

Landing gear shimmy primarily involves simultaneous fore-aft, lateral, and yaw motion of the gear, although it can excite all modes of the gear. Shimmy results from interaction between the landing gear (and related aircraft structure) and the tire. The tendency to shimmy may also be affected by the vertical loading on the gear. During shimmy the axles describe a sort of figure-eight motion as the airplane rolls down the runway.

A shimmy analysis of the main gear should be performed. Insufficient stability margin should be a cause for concern. Brake torque and brake forces at a constant level are generally considered to improve shimmy stability margin. However, antiskid must modulate brake torque as it constantly seeks the skid level. Gear oscillation may feedback to the antiskid controller through wheel speed. If the gear is only marginally stable, and is close to the edge of self-generated oscillations, antiskid may push it over. To avoid this, antiskid may have to be detuned, resulting in less efficient stopping performance. In this case, antiskid stopping efficiency requirements should be relaxed.

The targeted stability margins should reflect the state of the art of shimmy analysis and simulation, which is not yet sufficiently predictive for aircraft and antiskid designers to be entirely confident in its results.

If a shimmy damper is used to improve shimmy stability, a tolerance analysis should be made to ensure that production shimmy dampers behave as expected.

The gear structure, in combination with the related aircraft structure to which the gear is attached, should be designed so that lateral, fore-aft, and yaw modes of vibration are not too close to each other in frequency, to avoid motion in one mode from exciting the others.

Single wheeled, cantilever gears, may be most susceptible to shimmy type motion in combination with antiskid modulation, as braking forces may tend to twist the gear about the shock strut axis, causing the axle and wheel to not be aligned with the direction of travel of the airplane (see Figure 15). If the wheel is not aligned with the direction of travel, the tire will have to twist to compensate, thus producing side loads and twisting moments on the gear. This can lead to shimmy-like behavior during antiskid cycling, and may cause antiskid cycling if antiskid is not tuned to ignore the variation of wheel speed caused by the tire twisting. Note that a severe enough twist angle will cause the tire footprint to slip relative to the runway. Once the tire slips relative to the runway, the tire-runway coefficient of friction will drop (backside of the mu-slip curve) which, if antiskid is operating near the peak of the mu-slip curve, will produce a skid. Antiskid, will reduce brake torque to allow the wheel to recover from the skid and this in turn will feed back into the tire and gear, possibly resulting in repeated skids and brake releases. Antiskid must be tuned to avoid this behavior. Figure 13 shows both longitudinal friction and cornering friction as a function of wheel slip ratio.

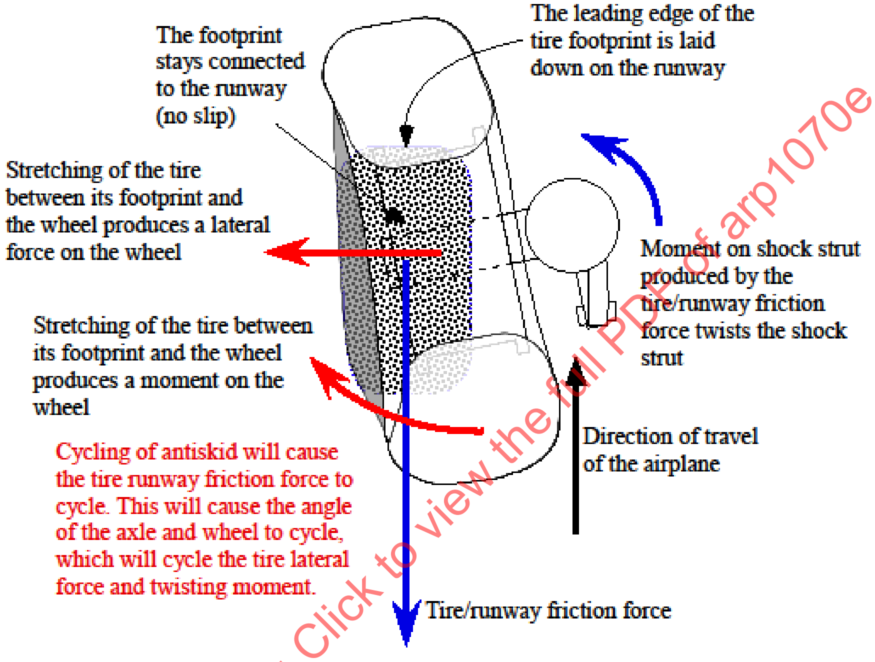

Figure 15 - Tire twist

5.1.12 Directional Control

All airplane aspects that contribute to directional control should be considered as a whole, along with antiskid and brake control. Such aspects include:

- Wheel base (distance from main gears to the nose gear).
- Wheel track (lateral distance between left and right main gears).
- Nose gear steering.
- Aerodynamic steering.
- Differential braking.

Aircraft with design aspects that result in more difficulty with directional control may require antiskid that is not optimally tuned for the best possible stopping performance.

5.1.13 Passenger Comfort

In some cases, smooth brake control and passenger comfort may be a more important consideration than antiskid stopping performance. This might be the case with some business jets. In these cases, antiskid should be tuned to minimize pressure cycling that can be felt or heard by the passengers.

5.2 Antiskid Integration Interaction with Other Aircraft Systems

5.2.1 Integrated Modular Avionics

Placing the antiskid controller in an integrated modular avionics (IMA) rack presents particular problems for antiskid development, integration, and troubleshooting. Two types of IMA are considered:

1. Antiskid shares processor time with other aircraft functions.

2. Antiskid has dedicated cards in the IMA rack.

In both cases, integration of antiskid may be problematic. The airframe manufacturer should ensure that the antiskid supplier is provided with equipment and an IMA integration environment that is sufficient for antiskid integration. Factors to consider include:

1. Cost.

2. Standard I/O bus so that the test environments created by the antiskid supplier can readily simulate inputs to the antiskid control that would normally be received from the aircraft (weight on wheels, aircraft speed, etc.), as well as receive outputs from the antiskid control that go to devices on the aircraft like cockpit displays and maintenance computers. Note that large portions of antiskid integration may take place in a full HITL simulation environment where the simulation computer takes the place of the aircraft in supplying information like weight on wheels and aircraft speed to the antiskid control.

3. A well-defined and easy to implement integration environment.

Sharing a processor is problematic to the antiskid suppler for a number of reasons:

1. Antiskid is processor intensive. As antiskid algorithms improve, and as the number of auxiliary functions connected to antiskid increase, it becomes more processor intensive.

2. The wheel speed sensor is no longer connected to a brake control unit that is specialized for interaction and calculation of wheel speed from that sensor. The most important input for antiskid now comes from an outside source.

3. BITE (built-in test equipment) and built-in test software becomes more problematic to design, test, and troubleshoot.

4. Troubleshooting, in general, will be more difficult. As the antiskid supplier no longer has control over all of the hardware and the related I/O, nor overloads on the processor not related to antiskid, troubleshooting will cross many suppliers. This has the potential to increase by orders of magnitude the time it takes to troubleshoot.

5. Software verification activities may be increased by orders of magnitude as changes in software for aircraft functions other than antiskid may require reverification of antiskid software.

IMI implementations of antiskid must be validated according to DO-178 (along with DO-248 clarifications) and DO-254.

5.2.2 Communications Buses

Standard communications buses and protocols should be used as much as possible. Non-standard communications buses and protocols can increase the difficulty of creating the hardware and software environment for antiskid system integration.

5.2.3 Cockpit and Maintenance

The antiskid system failure indication should be provided in the cockpit, as a message through the Crew Alert System, or a discrete “inop” warning lamp preferably mounted in a prominent location within the pilot’s field of vision during the landing and braking phase of flight, to indicate that there has been a system malfunction. Annunciation of system malfunction should be considered during the system design to preclude unsafe pilot reaction to minor system faults.

If an electrical on/off switch is incorporated into the design, the switch inoperative failures mode or antiskid off mode should be made clearly visible to the pilot.

The failure detection logic should be of the “passive” type; that is, it will function to provide failure indication, visual or audio, without altering remaining skid control capability. The antiskid system should fail with “brake clamping force as metered by the pilot,” except for systems with four or more control valves, where the affected wheel may be isolated (made to free roll).

The cockpit failure indication system should be designed so that the antiskid control unit drives indication off, so that a disconnected or removed controller annunciates a fault.

5.2.4 Hydraulics

5.2.4.1 Fluid Cleanliness and Filtration

Antiskid valves can be adversely affected by fluid contamination. Filters should be included on the inlet and brake ports to protect the valve.

5.2.4.2 Leakage

Requirements for leakage of antiskid components should take into account the architecture and operational profile of the entire braking hydraulic system. Leakage lower than is possible for the proposed antiskid valves should not be specified.

6. ANTISKID REQUIREMENTS

6.1 Stopping and Cornering Performance

The antiskid system, in conjunction with the aircraft brake system, should be capable of functioning efficiently under all runway conditions from maximum rolling speed to the lowest speed compatible with ground handling of the aircraft.

The system should be tuned for optimum braking performance throughout the control speed range over a broad range of operational conditions, including a variety of runways such as dry, wet, icy, etc.

The system should typically provide braking efficiencies in the order of 90% or better. Efficiency goals will be dependent on the needs of the particular aircraft. In some cases, directional control ability, tire wear, or some other criteria may be more important than stopping efficiency and stopping distance. Antiskid efficiency calculation methods are defined in AIR1739. Developed mu efficiency (AIR1739B, 5.2.2) and developed acceleration efficiency (AIR1739B, 5.2.4) are the preferred methods. Developed mu efficiency is a measure of antiskid efficiency alone. Developed acceleration efficiency is a measure of total aircraft stopping performance, including aerodynamic effects, engine effects, etc.

Efficiency requirements for antiskid should not be set higher than what is possible given the design of the aircraft. See, in particular:

- 5.1.1 (Braking System Response)
- 5.1.4 (The Touchdown Event)
- 5.1.8.1 (Brake Response)
- 5.1.8.3 (Brake Friction Properties)

- 5.1.9 (Aircraft Hydraulics (Hydraulically Actuated Braking System))
- 5.1.10 (Tires)
- 5.1.11 (Landing Gear)

The system should operate in such a manner as to maintain tire cornering capability.

The antiskid system should not impair the pilot's ability to apply and release the brakes or adversely impact the controllability of the aircraft.

Both stopping ability and directional control are dependent upon available friction (μ) between the tire and runway as well as the weight on the wheels.

Skid level in a hydraulic system is typically defined as the brake pressure above which a skid will occur. With an electric brake, the skid level is the clamping force above which a skid will occur. As the brake torque gain, the weight on the wheels, and the tire-runway coefficient of friction change continuously throughout a stop, the skid level constantly changes as well.

A typical tire braking force (friction) wheel slip characteristic is shown in Figure 16. With increasing brake clamping force, the tire is forced into an incipient skid, in which the tire begins to traverse onto the "back side," or the negative sloped portion, of the μ-slip curve (tire braking curve). A typical friction coefficient versus slip curve is also shown in Figure 1.

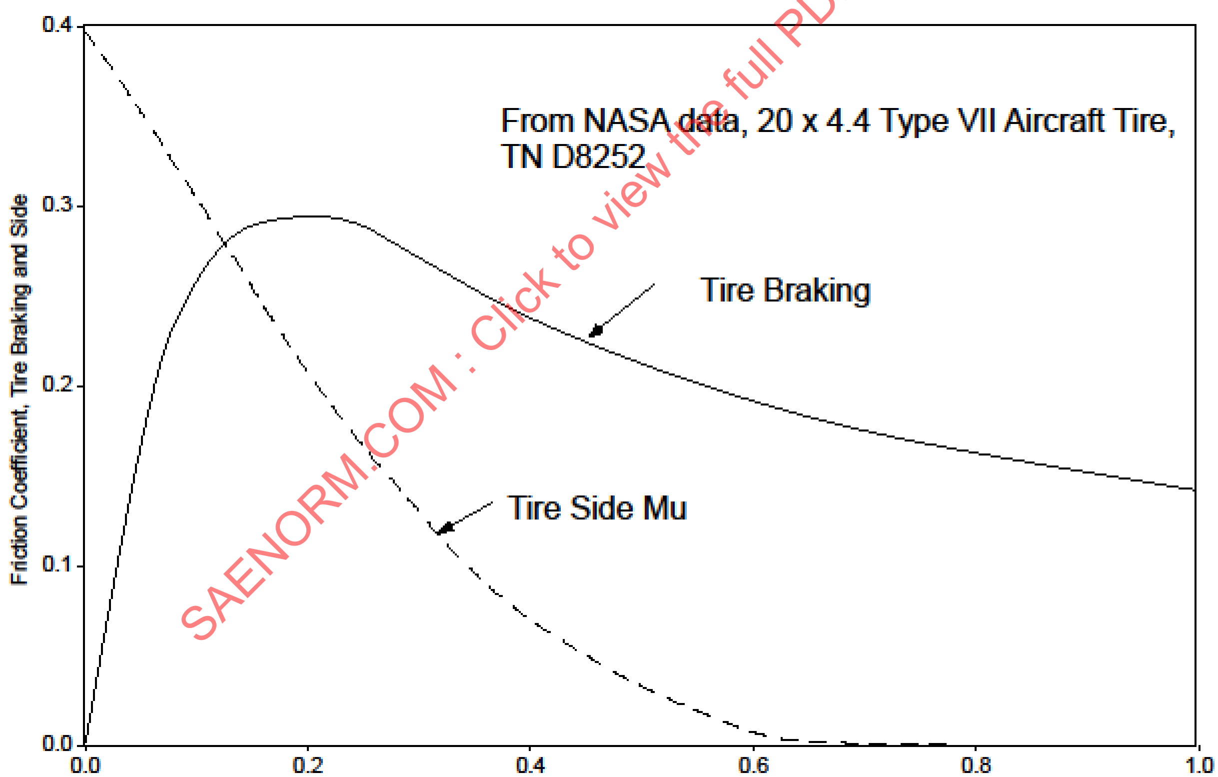

Figure 16 - Friction coefficient, tire braking and side, fixed wheel yaw angle

With increasing brake clamping force, the tire is forced to the peak of the mu-slip curve and over onto the "backside," or negatively sloped portion of the curve, at which point a skid will occur. The antiskid system should utilize some means to detect the skid level, and modulate the brake clamping force near that level, in a narrow range near the peak of the braking force curve. To maintain cornering capability, the control should prevent large excursions onto the backside of the mu-slip curve.

Additional, specific areas that need to be addressed are:

a. Rapid initial adjustment to the optimum control clamping force.

b. Operation at partial metered clamping force levels.

c. Rapid adjustment to changing runway conditions.

d. Control of high onset brake clamping force (spikes).

Since the total braking function involves more than the antiskid system and wheel, brake and tire assemblies, determination of the total airplane stopping performance is usually the responsibility of the airframe manufacturer.

Methods for "tuning" antiskid to meet these objectives are discussed in Section 8.

6.2 Landing Gear Stability

The antiskid system should not induce nor be adversely affected by landing gear instabilities. As this is a system issue, see 5.1.10.4; all of the interested parties should share responsibility. Refer to AIR1064. Note that slow braking system response, as described in 5.1.1 and 5.1.9, may reduce or eliminate antiskid's ability to meet this recommendation.

The antiskid system should not induce any adverse loads on the landing gear structure or the airframe. The system should not induce any undesirable motion or dynamic instability in the gear or airframe such as gear walk, truck pitch, or airplane pitch. Note that the antiskid system should not be considered to be a damping system with the capability to actively damp out vibrations induced by system dynamics external to the antiskid system. Consensus on the allowable magnitude and frequencies of oscillations should be included in the antiskid requirements documentation.

In view of the fact that some skid control cycles result in oscillatory loading of the landing gear structure, it is considered good practice to perform analysis to show that the oscillatory or torsional loading resulting from skid control cycles does not cause structural damage to the landing gear or airframe. The following variables are considered pertinent to this analysis.

a. Antiskid system response characteristics.

b. Brake assembly response characteristics.

c. Brake system response characteristics (hydraulic system response or electric power system response characteristics).

d. Airplane gross weight and moments of inertia.

e. The elastic and damping characteristics of the landing gear.

f. Airplane aerodynamic characteristics.

g. Pilot initiated actions (pedal braking, adjustment of aerodynamic surfaces, etc.).

h. Tire to runway friction for various tire tread and runway conditions.

i. Tire pressure.

j. Tire stiffness characteristics.

k. The brake's pressure versus torque characteristics and variations in brake frictional coefficients resulting from different energy levels.

l. Brake system command pressure characteristics.

m. Elastic (stiffness) and damping characteristics of the tires.

n. Aircraft directional response and characteristics.

o. Landing gear natural frequency (fore/aft, torsional).

p. Landing gear vertical suspension capability (shock strut damping, stick slip due to bearing side loads, shock strut spring curve).

q. Brake/wheel structural characteristics and natural frequencies.

6.3 Aircraft Pitch Excitation

The antiskid system should not introduce any undesirable airplane pitching characteristics.

Note that slow braking system response, as described in 5.1.1 and 5.1.9, may reduce or eliminate antiskid's ability to avoid excitation of aircraft pitch.

Steps in the shock strut or a sticking shock strut, as described in 5.1.11.2, may also reduce or eliminate antiskid's ability to avoid excitation of aircraft pitch.

6.4 System Features

The following features may be required for the system in addition to the basic skid control functions depending upon the aircraft configuration and landing distance requirements. The procurement specifications will define the type of system and the performance criteria required.

6.4.1 Touchdown Protection

The system should provide continuous release of brake clamping force where there is the possibility of applying brake clamping force before wheels are on ground, rotating, and ready for braking strut compression with wheel rotation override intelligence is normally employed to determine the aircraft is on the ground and wheels are rotating and ready for braking. In selection of touchdown protection, the probability of introducing additional failure modes and failure points should be considered.

6.4.2 Locked Wheel Protection

The system should incorporate means to release clamping force to the brake for any wheel which is rolling at a speed some preset fraction of the best available measure of equivalent airplane speed. The system shall release brake clamping force until the situation is corrected. The preset amount should preclude the release of brakes during normal turning maneuvers.

6.4.3 Hydroplaning Protection

Hydroplaning protection provides an extended release of clamping force to a braked wheel which fails to spin up due to hydroplaning at high speed on a flooded runway. Hydroplaning protection may be implemented in a number of ways, including:

- The use of an airplane ground speed reference which is external to the antiskid system, such as an inertial reference system. Brake release is based on the wheel speed being less than a set percentage of the ground speed reference. This method of hydroplaning protection also provides touchdown protection as well as protection against hydroplaning that occurs in the middle of a stop, well after touchdown.

- A combination of “weight on the wheels” signals, a properly chosen delay function and comparison with the wheel speed of trailing wheels (where available).

6.4.4 Emergency Operation

The antiskid system needs to function only on the normal braking system. The backup brake system, if used, should meet the minimum requirements as stated in the procurement specification. It should be possible to stop the airplane with the antiskid system turned off. Refer to 14 CFR 25.735h.

6.4.5 Parking Brake

If a parking brake is present, the antiskid system should consider those issues related to parking, such as antiskid valve leakage and incorporation of park brake equipment into the HITL setup as needed.

6.5 Wheel Speed Transducer

The wheel speed transducer is the primary feedback to antiskid control. The antiskid controller should be paired with the wheel speed transducer such that a highly accurate measurement of wheel speed can be made during every antiskid control cycle.

A wheel speed sensor should be provided at each braked wheel or group of braked wheels which are restrained to rotate together to assure detection of incipient skids. The wheel speed sensor installation should assure accurate sensing of wheel angular motion. In most cases, constant velocity coupling between the wheel and wheel speed sensor should be provided to remove any velocity effect resulting from offset between the centerlines of rotation.

Wheel rotation sensing devices are generally located within the wheel axle or in areas adjacent to the wheel. Axle housed units are usually subjected to brake heat. Those mounted on the brake or adjacent to the wheel may be subjected to brake heat and/or outside elements such as rain, slush, etc.

The effects of vibration, concentricity and tolerances on the accuracy of detection of the actual wheel motion needs to be considered in the design of wheel speed sensing devices and their installations.

Attention should be paid to the failure modes and wheel speed transducer susceptibility to EMI and vibration.

Wheel speed transducers are discussed in more detail in AIR1739.

A number of different types of wheel speed detectors are presented below. Note that this list does not preclude the use of new and different technology for detection of wheel speed.

6.5.1 Inertia Type

Hub cap or rim driven rotating masses on overriding clutches operating switch(es) or hydraulic/pneumatic valve(s). This type of transducer is not suitable for modern antiskid systems.

6.5.2 DC Generator

DC generators have an output DC voltage signal respectively as a function of wheel speed.

6.5.3 AC Inductive Type Generator

Most modern antiskid systems use an AC generator. The AC generator produces an output voltage signal with 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. These transducers can measure speed down to 5 to 10 knots, depending on tire radius and number of teeth. Below this speed, wheel speed cannot be reliably calculated. Neither can this type of transducer distinguish between forward and backwards wheel rotation.

A typical AC generator type of wheel speed transducer is mounted, and fixed, to the axle. It requires some sort of coupling from its rotor to the wheel hubcap. The coupling should be designed to compensate for any misalignment between the axle centerline and the rotational axis of the wheel. It should be stiff enough and have enough damping to prevent spurious dynamics causing wheel speed mismeasurement from twisting and bending of the coupling.

An alternative arrangement is a two-piece unit (sensor-exciter ring), in which one piece is stationary and mounted in the axle with the second unit mounted in and rotating with the wheel or hub cap. If a two-piece unit is used, special attention must be given during installation to air gap tolerances, and effect of wheel deflection to provide suitable signal amplitude compared to controller input saturation for reliable wheel speed detection. Producing a wheel speed signal sufficient for modern antiskid with this arrangement may be extremely difficult to impossible.

Figure 17 shows the toothed rotor/stator arrangement of an AC generator wheel speed transducer. As the rotor rotates, the teeth come into and out of alignment. The magnetic coupling and decoupling associated with the teeth coming in and out of alignment generates an approximately sinusoidal wave shape. A poorly designed coupling between the hubcap and the rotor (with free play or too low a spring rate and low damping) can result in rotor oscillations relative to the hubcap which can produce spurious wheel speed pulses.

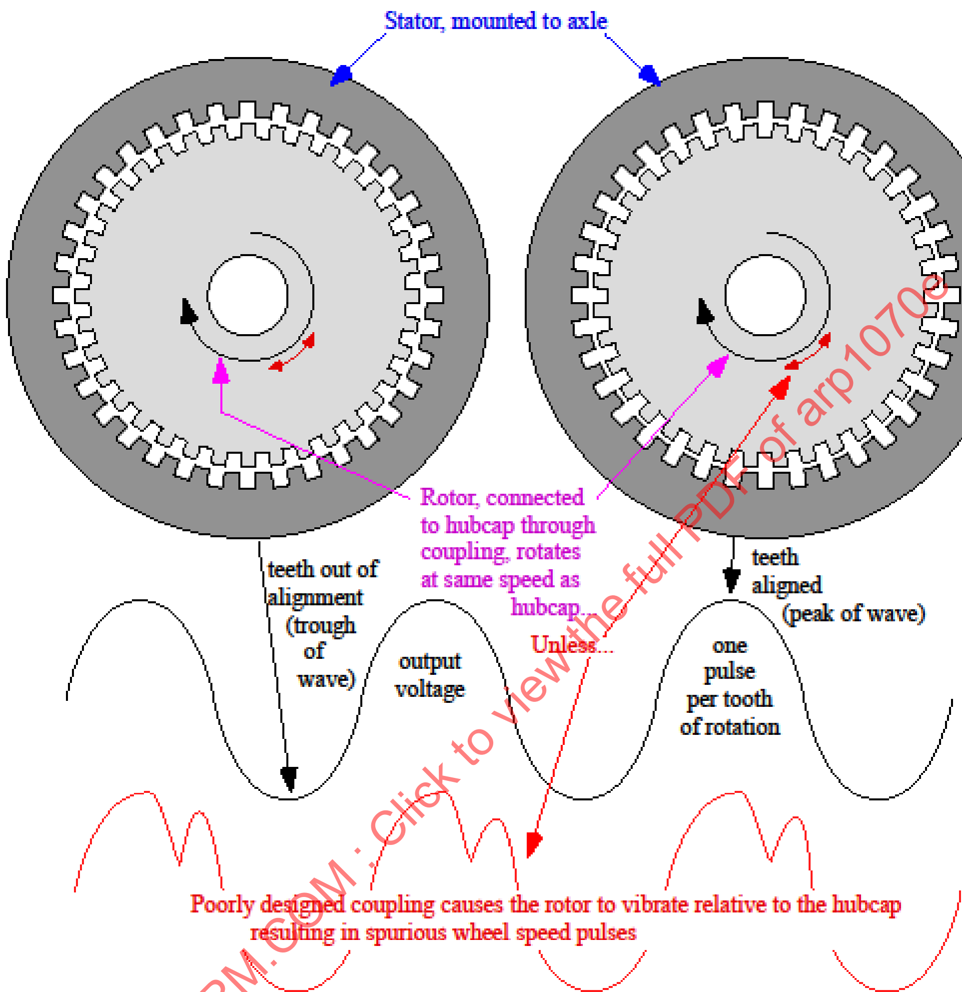

Figure 17 - Wheel speed AC generator

6.5.4 Optic Sensor

Optic sensors are used in conjunction with fiber optic inputs and output. Optic sensors contain some method of reflecting or interrupting the light input from a light source. The modified light signal is returned to the controller through the fiber optic cable. Separate input and output lines are recommended. This sort of sensor is rare, but has been used successfully with modern antiskid. Use of this sort of transducer may be appropriate when there are significant magnetic fields in the vicinity of the axle that might cause problems with AC inductive generator transducers.

6.5.5 Hall Effects Transducer

Another wheel speed transducer that has recently appeared on a production airplane is a Hall effects based transducer. Hall effects sensors include a ring of magnets attached to the hubcap which interact with a ring of hall effects sensors attached to the axle. This transducer is contactless and requires no coupling to a hubcap. Advantages of the Hall effects transducer include the ability to measure wheel speed down to zero and to distinguish between forward and backward wheel rotation.

6.6 Runway Condition

The antiskid system should be able to adapt to the full variety of runway conditions that will be seen in service. These include:

- Irregular roughness.
- Regularly spaced concrete slabs.
- Slope.
- Crowning.
- Paint stripes.
- Water and ice patches.
- Contamination, tire rubber, hydraulic fluid, water, ice, etc.
- Grooved.
- Ungrooved.

The procurement specification should detail the scope of the efficiency requirement relative to runway condition.

6.7 Atmospheric Condition

The antiskid system should be able to adapt to and operate under variations:

- Temperature.
- Altitude.
- Wind, from any direction.
- Precipitation.

6.8 Design and Construction Goals and Considerations

6.8.1 Hydraulic Equipment - General

It is recommended that hydraulic components conform to the applicable requirements of AS8775 Type II equipment and 14 CFR 25.1435.

Hydraulic units should operate satisfactorily with the specified hydraulic fluid, filtered and controlled to a contamination level of Class 9 or other value per NAS1638 as specified by the airframe manufacturer. All testing should be accomplished with the specified operating fluid.

Operating temperatures should be considered according to the procurement specification and regulatory requirements.

Hydraulic units should function satisfactorily over the full range of aircraft supply pressure and return line pressure.

6.8.1.1 System Flow

Initial consideration should be given to provisions for decreasing brake release time. Subsequent analysis should show that components of the skid control and hydraulic brake system, when functioning together, are capable of achieving the required skid control cycle. This analysis should take into consideration possible limited hydraulic capacity which may adversely affect the braking system when combined with the flow rates that occur during skid control cycling. Extremes of operating temperatures, which will be encountered during the operation of the airplane, should also be considered in this analysis. Particular attention should be devoted to return line capacity to ensure adequate antiskid response can be achieved.

6.8.1.2 Brake Metering Valves

The valve should be designed to provide smooth metered pressure with increasing pedal load/travel. Valve ports and internal fluid passages should be sized to permit adequate flow to and from the skid control valve. Consideration should include initial brake response in addition to subsequent cyclic reapplication of pressure by the skid control valve. Additional consideration should be given to the metering valve's compatibility relative to the demands placed upon it by skid control valve in the application and release of brake pressure associated with skid control.

6.8.1.3 Skid Control Valve

The valve should be designed so as to result in adequate step and frequency response when incorporated into the aircraft braking hydraulics system.

It is recommended that valves be designed in accordance with the applicable requirements of the procurement specification and ARP490 and be suitable for the brake control system environment with special emphasis upon contamination tolerance, stability with life and temperature, tolerance to service handling, and moisture sealing.

In systems where an accumulator is used for parking or as a stored passive energy device and the antiskid servo valve supply port is not isolated from the accumulator when brake pressure is not commanded, internal leakage of the skid control valve, which would bleed down accumulator pressure, should be minimized. However, consideration should be given to any reduction in valve performance that may result from reduced internal leakage.

It is considered good practice to perform studies to determine the effects of the skid control valve locations upon antiskid system response time, hydraulic tubing complexity, weight and cost, and hydraulic system maintainability. Antiskid system performance is usually enhanced if the skid control valve is mounted as close as practical to the brake being controlled.

These units are generally installed in the wheel well or within the fuselage adjacent to the wheel well. However, they should not be mounted on the landing gear unsprung mass without giving adequate consideration to the following:

a. The increased severity of the vibration spectrum.

b. Increases in airplane wiring weight.

c. Increases in hydraulic system complexity due to installation of additional return line including hose and swivels.

d. Increased vulnerability to foreign objects thrown up by the tires and to damage from a tire carcass in the event of tire failure.

e. Increased gear inertia loading.

6.8.2 Hydraulic Lines

It is recommended hydraulic lines and fittings be designed to minimize restriction of flow with the objective of optimizing skid control response time. However, one-way restrictor or flow regulators may be used to reduce initial pressure-on rate when required. Before installation on the aircraft, the effect of these restrictors should be considered in hardware-in-the-loop simulation.

a. Size: Hydraulic lines for supply and return should be selected to provide minimum pressure drops compatible with flow requirements of the brake metering valves, skid control valves, and brake assemblies under installed environmental conditions.

b. Type: Hydraulic tubing, rather than hoses, should be installed downstream of the brake metering valves where possible to minimize the accumulator effect during pressure changes.

c. Parking Requirements: System parking requirements should recognize internal leakage of the skid control valve. Shutoff valves may be used to block quiescent flow to system return. Parking brake pressure should be maintained in a manner such that thermal expansion and contraction of the hydraulic fluid is compensated. Otherwise, the brake can be seriously over pressurized or can lose parking torque due to pressure reduction.

d. System Bleeding: Provisions should be incorporated to minimize entrapped air within the system. Reverse bleeding of the system should be limited to those installations which provide adequate internal or external means to prevent entry of contaminants into hydraulic components. Some skid control valves, for example, can be rendered inoperative if contaminants reach valve spools and orifices. Self-contained inlet filters in these control valves are not effective during reverse bleeding. System designers should consider location of bleeder valves, integral bleeding devices, and number of personnel plus equipment necessary for proper system bleeding.

e. Hydraulic fuses: Hydraulic fuses in the lines should be considered to prevent breaks in the lines between the antiskid valve and brakes from dumping the system hydraulic fluid and to prevent fluid discharge onto hot brake assemblies. Refer to 14 CFR 25.735b2.

6.8.2.1 External Leakage

External leakage should be minimized under all operating temperature and pressure conditions.

6.8.3 Electrical Design

The system's airborne electronic hardware shall comply with the guidelines provided by RTCA DO-254 in the scope of FAA AC 20-152.

6.8.3.1 Control Unit Configuration and Location

It is considered good practice to perform design studies to determine if overall advantages in airplane wiring weight and/or cost can be obtained by packaging the control unit components in more than one box. The control unit should be readily accessible to facilitate electrical checkout and, if possible, should be installed in a temperature and pressure controlled environment of the aircraft to minimize need for temperature compensation.

6.8.3.2 Electric Power Requirements

It is recommended the antiskid system should conform to all applicable requirements of the procurement specification, and should give specified performance from the power source configuration specified in the detail specification. Consideration should be made for dealing with out of specification aircraft power. Addition of new or upgraded antiskid systems to older aircraft should comply with the power quality standards present on the aircraft, and not the latest version of the applicable standards documents.

During transient power interruption the system should not fail or revert to "brake pressure as metered by the pilot." Control system performance, after sustained loss of power and/or reapplication of power, is to be defined by the procurement specification. Sufficient redundancy and isolation should be maintained to minimize total system and asymmetrical failures.

The antiskid supplier should anticipate that fluctuations in aircraft power may be greater than those specified by the airframe manufacturer.

6.8.3.3 Electromagnetic Interference (EMI)

Consideration should be given to EMI design requirements sufficiently early in an antiskid system design program to preclude operational problems on the aircraft.

EMI tests should be performed on the antiskid system installed in a simulated aircraft network. EMI compatibility should be demonstrated on aircraft, as well as simulated aircraft network, as part of normal aircraft testing. Equipment should be protected against lightning strikes.

6.8.3.4 Wiring

External wiring should be installed in accordance with MIL-W-5088 and should be of the type specified in procurement specification or AS22759. Internal wiring should be compatible with accepted industry standards and the configuration. Appropriate protection from external noise should be provided for sensitive circuits such as the wheel speed sensing circuit.

6.8.3.5 Connectors

External connectors should be environmentally sealed, high vibration resistant, screw type connectors. The largest pin sizes should be used whenever possible and the maximum spacing maintained between the pins. When connectors are located in close proximity on the same unit (valve modules, control units, etc.), positive means to prevent misconnection, such as different shell size, wire routing, or clocking connectors, should be considered.

6.8.3.6 Environmental Stress Screening

Components should be capable of successfully completing environmental stress screening tests as part of the acceptance test program.

6.8.4 Environmental

The environment in which the components should operate individually and as a system should be compatible with the aircraft installation environment and tested according to RTCA DO-160 or MIL-STD-810, as determined by the airframe manufacturer.

The environmental limits under which antiskid should function and the extended limits under which the antiskid system components should survive without damage should be identified by the airframe manufacturer in the procurement specification.

The basic function of antiskid is to stop the airplane, which happens only on the ground, and only after an accelerated stop, a rejected takeoff, or a landing. The normal and reasonable sequence of events leading to aircraft stops should be considered when specifying the environmental limits for antiskid system components.

Antiskid components are located in different areas of the aircraft. For example:

- Valves are often (although not always) located in the wheel well.
- Brake control units are generally located in protected avionics bays.
- Wheel speed transducers are generally located within the axle.

The location of each component should be considered when specifying the environmental limits.

Environmental conditions that should generally be considered for antiskid components include:

- Temperature and altitude.
- Temperature variation.
- Humidity.
- Operational shocks and crash safety.
- Vibration.
- Explosion atmosphere.
- Sand and dust.
- Fungus resistance.
- Salt spray.

6.8.4.1 Acceleration

The antiskid system should function properly when exposed to translational accelerations consistent with those encountered on the aircraft.

6.9 Software Development

Virtually all modern antiskid systems employ digital microprocessors. If the brake controller incorporates digital microprocessor technology, software development and testing should be done in accordance with the design specification and should comply with the guidance for the appropriate software level of RTCA DO-178 along with the clarifications in RTCA DO-248. If the brake controller incorporates digital microprocessor technology, software documentation, and testing should be done. This includes all the following phases:

a. Documentation of requirements, design, and coding.

b. Code execution.

c. Performance, timing, and data handling.

d. Built-in test equipment (BITE) tests.

e. Failure response tests.

Code analysis and documentation versus part checks ensure that software is properly coded and implemented. Code execution, performance, timing, and data handling tests are done on the simulator. These tests ensure that the controller performs as intended. BIT check and failure response checks ensure that BIT monitors the operation status and detects the faults.

If the controller incorporates digital technology, built-in-test (BIT) procedures must be incorporated in the code. The BIT system should be capable of detecting critical faults with 95% or greater confidence level and it should not compromise the operation of the antiskid or the auto brake system (if used). The detected faults should be isolated to a replaceable unit. Software management and discipline must be employed to ensure control of configuration and proper validation.

7. COMPONENT TESTING AND EVALUATION

Testing of individual components of the antiskid system equipment provides valuable data for assessing the total system performance and environmental compatibility. Laboratory test data on brakes, antiskid valve, and metering valve characteristics, etc., are useful in developing an overall simulation of the brake control system. Component tests should demonstrate operational compatibility throughout environmental ranges.

Component testing and evaluation can be broken into:

a. First article inspection.

b. Environmental tests.

c. Endurance tests.

d. Hydraulic tests.

e. Performance tests.

7.1 First Article Inspection

Prior to the testing of any component, a first article conformity inspection should be performed. Each antiskid LRU (line replaceable unit) should be examined to determine compliance with the requirements of the specification provided by the airframe manufacturer and the detail specification with respect to materials, workmanship, dimensions, weight, and markings.

7.1.1 Environmental Tests

Unless otherwise specified in the detail specification, the antiskid components should be subjected to environmental tests in accordance with RTCA DO-160 or MIL-STD-810, and as specified herein.

The following sections describe additional tests or test conditions particular to antiskid brake control systems.

7.1.1.1 Vibration

Mounting (mechanical, electrical, and hydraulic) should simulate aircraft installation. Wheel-driven units should include an axle-hubcap simulation.

7.1.1.2 Combined Environmental Tests

In the event a combined environment is more severe than individual tests, consideration should be given to including such combinations in component evaluations.

7.1.2 Endurance Tests

The antiskid system components, installed in a simulated hydraulic and/or electrical network, as appropriate, should be subjected to the following tests.

7.1.2.1 Transient Cycling

The antiskid system components should be subjected to 20000 power-on transient cycles of electrical and hydraulic pressure impulse cycles at the rates specified in the detail specification.

A more rational duplication of transient cycling during repeated takeoff and landing profiles may be considered, if applicable.

7.1.2.2 Wheel Speed Sensor Flight Cycling

The wheel speed transducer should be tested through a number of flight cycles. The number of flight cycles should be determined by the airframe manufacturer. An example flight cycle follows:

a. Taxi out. (Constant wheel speed at typical taxi speeds.)

b. Short dwell. (Zero speed prior to takeoff.)

c. Takeoff roll. (Aircraft acceleration during takeoff roll to takeoff speed.)

d. Despin. (Typical despin deceleration rate. Decel rate may be limited by available test equipment.)

e. Short dwell. (Zero wheel speed.)

f. Landing spin up. (Typical wheel acceleration at touchdown. Acceleration rate may be limited by available test equipment.)

g. Landing roll. (Aircraft deceleration during a landing roll.)

h. Taxi in. (Constant wheel speed at typical taxi speeds.)

i. Short dwell. (Zero wheel speed.)

Aircraft acceleration, deceleration, takeoff speed, and landing speed may be adjusted to reflect different aircraft weights, altitude, air temperature, etc., for given percentages of the flight cycles.

5% of these cycles may be performed at a high temperature, to be determined by the airframe manufacturer in accordance with Section 4 of DO-160.

5% of these cycles may be performed at a low temperature, to be determined by the airframe manufacturer in accordance with Section 4 of DO-160.

7.1.3 Hydraulic Tests

Hydraulic components should be tested as specified in AS8775 or FAR 25.1435.

7.1.3.1 Additional Endurance Cycles for Hydraulic Components

In addition to the testing in 7.1.2, the hydraulic components should be subjected to additional endurance cycles in accordance with AS8775. The number of additional cycles should be determined by adding the maximum number of anticipated landings in the life of the gear and the maximum number of anticipated parking brake applications (when parking brake pressure is applied through the skid control valve) and multiplying the total by a safety factor of two. The hydraulic set-up should match the aircraft as closely as possible (hydraulic line sizes, lengths, components, etc.) when performing endurance testing.

Impulse qualification testing should equal or better real world environments.

7.1.3.2 Extreme Tolerance Analysis

The units used for pre-production component tests should be physically measured and the electrical output determined. These measurements should be compared with the proposed production tolerances. Based on performance of hydraulic leakage and electrical output exhibited during the component tests, the performance at the extremes should be analytically determined. Performance at the extremes should be within the limits identified in the detail specification.

7.1.3.3 Pressure Drop Test

The hydraulic units should be subjected to a pressure drop test in accordance with AS8775.

7.1.3.4 Fluid Contamination Tests

The hydraulic units should be capable of operating at least 10 hours when supplied with the specified hydraulic fluid contaminated to an appropriate class level of NAS1638. Contamination count should be made in accordance with ARP598.

All hydraulic components should be functionally endurance tested at maximum contamination levels allowed by the procurement specification to prove components function correctly (no jamming, hesitation, etc.) and do not fail prematurely.

7.1.3.5 Impulse Test

The hydraulic control units should be subjected to an impulse test at system operating pressure in accordance with ARP1383. Details of the test should be defined in the procurement specification.

7.1.4 Performance Tests

Performance tests of antiskid system components provide data essential to system level performance and evaluation.

7.1.4.1 Valve Tests

Flow and pressure gain characteristics of the metering and antiskid valves are useful in assessing the impact of the valve on system performance.

8. SYSTEM LEVEL ANTISKID PERFORMANCE AND SAFETY TESTING AND EVALUATION

The primary tools for accomplishing system level performance testing, antiskid tuning, and evaluation are:

a. Real-time hardware-in-the-loop (RTHITL) brake control simulation.

b. Dynamometer testing.

c. Flight test.

(a) and (c) are the primary tools for accomplishing system level performance testing and evaluation.

Man in the loop testing can be used in combination with RTHITL simulation to include pilot interactions with the system. Man in the loop simulation often uses models with lower fidelity than those used for antiskid tuning. Low fidelity approximations to full antiskid are often used in man in the loop simulations as well.

Dynamometer testing with antiskid in the loop is not required in the design of antiskid systems, as current and past systems have demonstrated. Dynamometer tests including antiskid in the loop are performed in some circumstances, typically in cases where investigation of the interaction between antiskid control and rotating hardware (brakes, wheels, tires, wheel speed transducers, wheel speed transducer couplings) is required and there is some question in the fidelity of the simulation (or suspicion of unknowns) in modeling the behavior.

Caution in the interpretation of the results of testing with antiskid in the loop on a dynamometer should be observed, as antiskid may perform differently on a dynamometer than it does on an aircraft. Note that the number of test cases is limited both by cost and the number of dynamometer stops that can be performed each day.

Prior to flight test, a letter certifying safety of flight should be prepared and submitted to the procuring agency.

8.1 RTHITL Brake Control Simulation

Computer simulation testing should be conducted to ascertain the degree of robustness that exists within the control loop of the antiskid system. Simulation tests should be devised to evaluate response over the entire envelope of aircraft braking operations.

Behavior important to assess includes:

a. Stopping performance and antiskid efficiency.

b. Gear fore-aft stability (gear walk).

c. Truck pitch (for gears with trucks).

d. Recovery from abrupt changes in the tire-runway coefficient of friction.

e. Response of the system to pilot pedal inputs.

f. Performance on contaminated runways.

g. Performance on rough runways.

h. Reaction to tire burst.

i. Touchdown protection.

j. Locked wheel protection.

k. Gear retract braking.

l. Response to spurious wheel speed.

m. Failure modes.

Parameters that should be adjusted over a range of values to accomplish that assessment include:

a. Aircraft weight and moments of inertia.

b. Center of gravity location.

c. Tire-runway coefficient of friction (mu).

d. Step changes in the tire-runway coefficient of friction.

e. Brake torque gain and shape of the brake torque gain curve versus energy or aircraft speed.

f. Gear stiffness.

g. Gear damping.

h. Partial pedal modulation.

i. Runway height versus runway position.

j. Aerodynamic device properties.

The components of a real-time hardware-in-the-loop (RTHITL) simulation are typically:

1. Simulation computer.
    a. Deterministic real-time operating system.
    b. A variety of input and output devices used to connect with real hardware.
2. Hydraulic simulator or electric brake simulator.
    a. Hydraulic lines, valves, brake.
    b. Electric brake, electric motion actuation controller.
3. Brake control/antiskid computer.

Figures 18 through 20 show examples of hardware-in-the-loop simulation set ups.

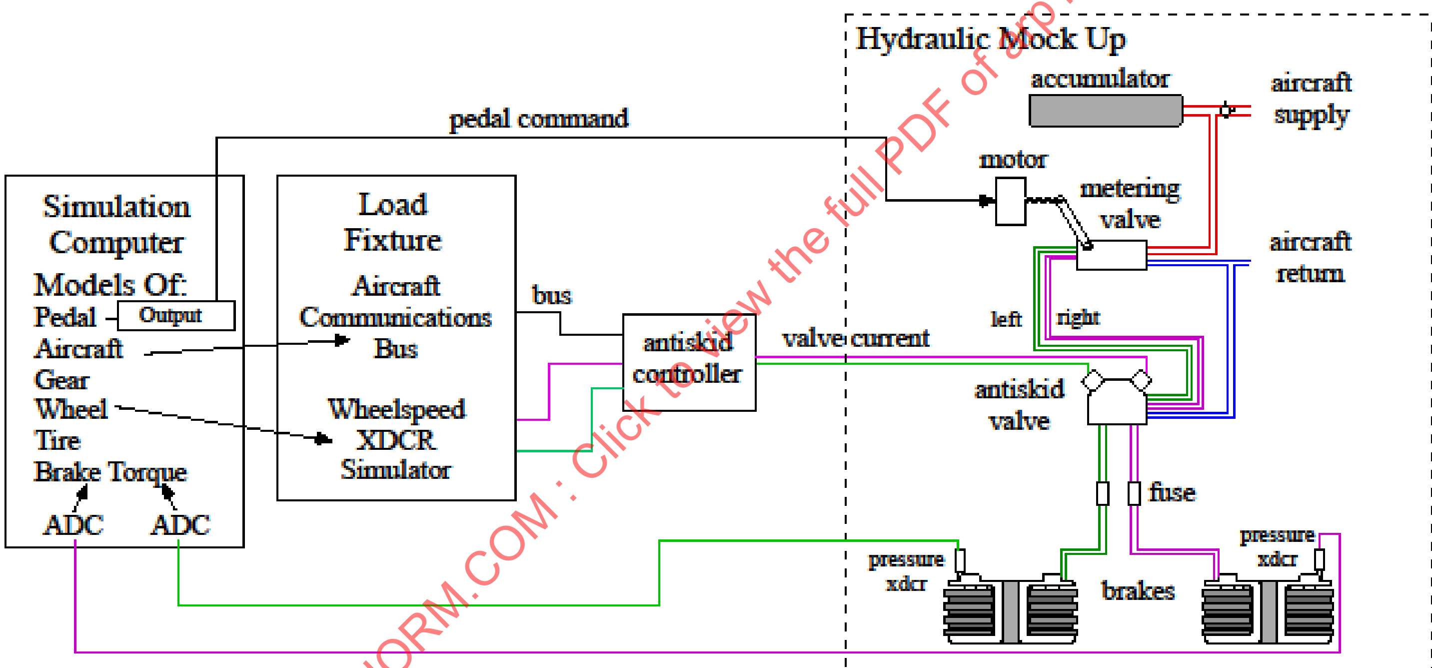

Figure 18 - Hardware-in-the-loop example, antiskid system

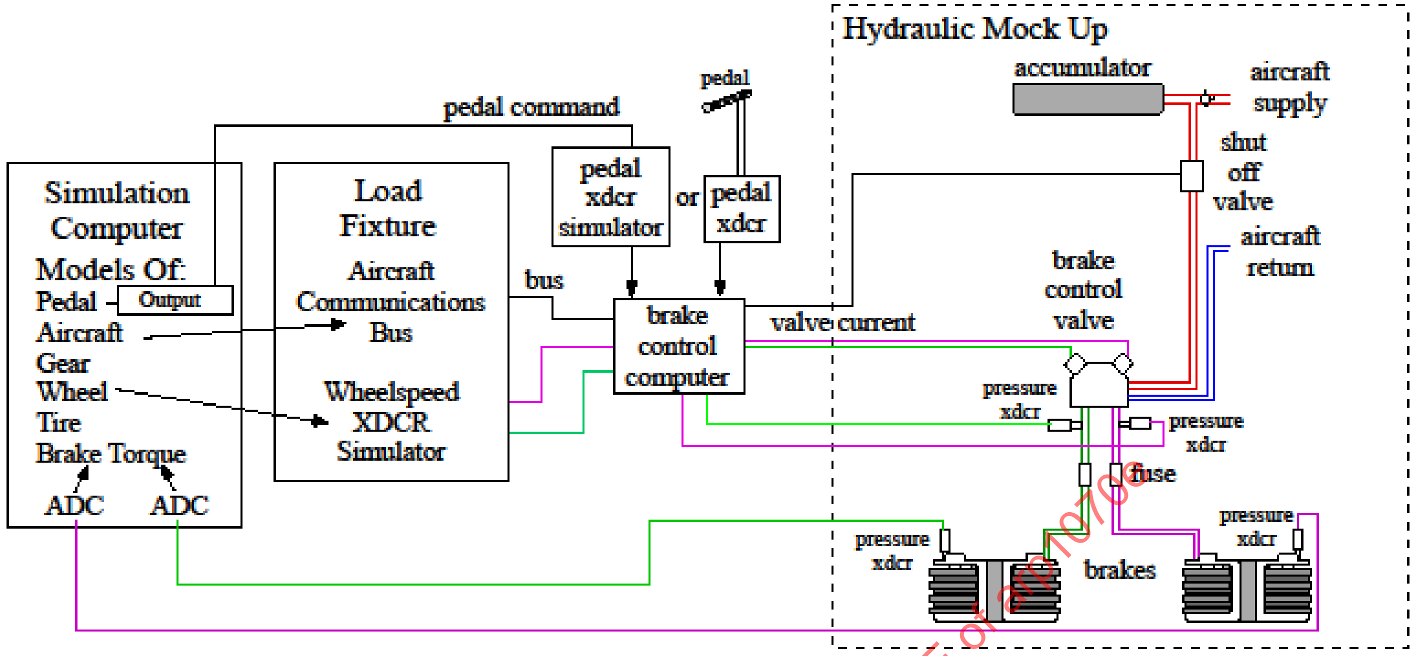

Figure 19 - Hardware-in-the-loop example, brake by wire system

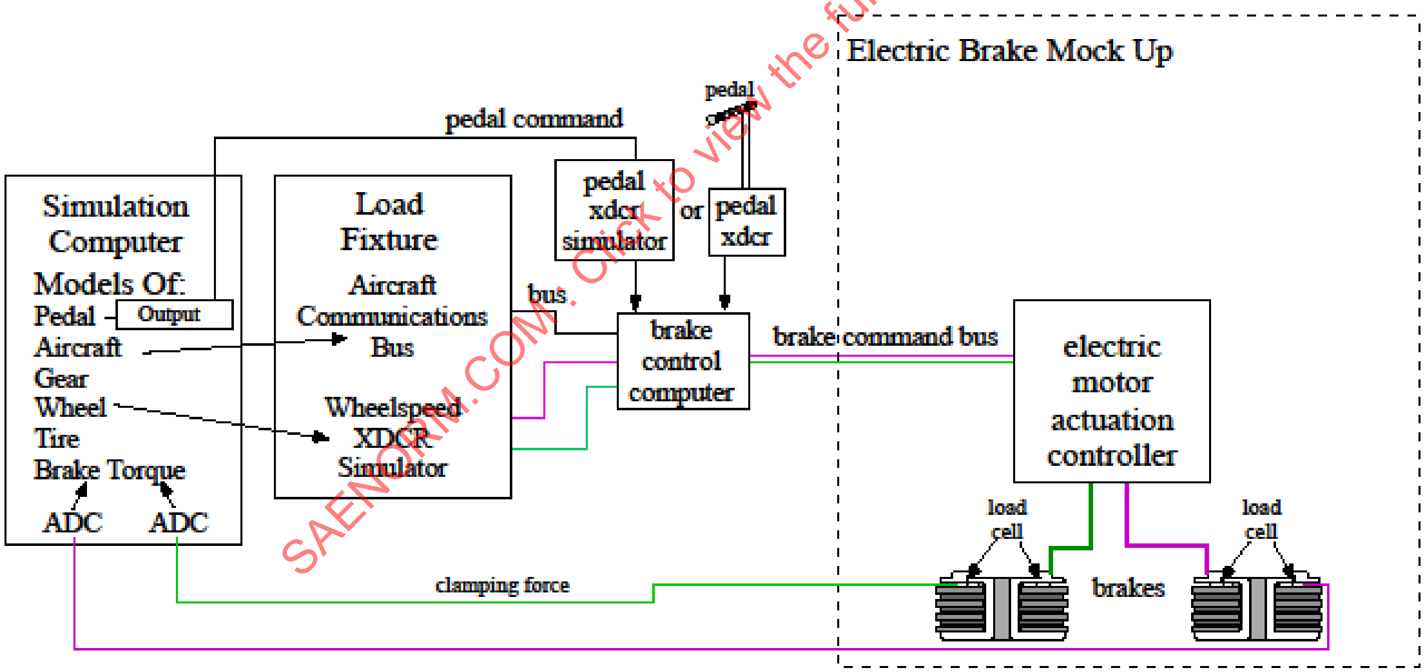

Figure 20 - Hardware-in-the-loop example, electric brake system

Brake Actuation: A mockup of the actual hydraulic system or electric brake system should be built and used as an integral part of the simulator. This is done to ensure the highest possible fidelity of brake actuation simulation. The present state of the art of real-time mathematical/digital simulation of hydraulic and electric brake actuation systems is not advanced enough or predictive enough for the purpose of antiskid development, integration, tuning, and testing, without significant use of physical mockups.

Hydraulic simulation rigs typically include all of the hydraulic components associated with the brake control system and is unique for each airplane. Use of the following hardware should be considered:

1. Brake metering valve(s) (for antiskid systems).

2. Non-rotating brake stacks and pistons.

3. Pump, accumulator, reservoir, and other components.

4. Representative lines and hoses between brakes, valves, and components.

5. Skid control valves.

Electric Power: If electrically actuated brakes are used, the simulator should provide the same electric response characteristics that are expected on the aircraft. Particular attention should be given to power output capability and reserve power characteristics.

The brakes should preferably be actual aircraft brakes, or a hardware simulation having the same stiffness and response characteristics. An objective of the hardware system is to achieve representative initial brake application, release, and transient response. Brake pressure or clamping force is measured and interfaced with a computer simulation of brake torque versus the input. The use of the mockup ensures accurate brake system response and allows detailed antiskid evaluation.

Prior to HITL simulation, frequency and step response tests should be run on the hydraulic or electric brake rig. A variety of full and intermediate steps should be run. Frequency response at several amplitude levels and DC command levels should be run.

Controller: During real-time testing, a prototype breadboard or an actual controller is in the simulation loop as shown in Figure 15. Wheel speed information from the computer is sent to the controller using a wheel speed sensor interface. In some instances, this can be replaced by an actual wheel speed transducer with a motor drive that is controlled by the computer to introduce the nonlinear effects of the wheel speed drive mechanism. In addition, prior to the availability of the controller card, a simulated model of the controller can be used to test and validate the computer simulation.

As the computational capability of modern processors improves, the potential to digitally simulate the braking system hydraulics and the brake control computer increases, although real-time, high fidelity, component level simulation of braking system hydraulics is still beyond current processors.

8.1.1 Aircraft Body Dynamics Simulation

Aircraft body dynamics, landing gear dynamics, tire/wheel dynamics and brake torque as a function of real brake pressure or brake clamping force are simulated by the simulation computer using mathematical models consisting systems of differential equations and supporting algebra and linked to the hydraulic or electric brake rig and to the brake control computer. Figure 21 shows a free body diagram of the airplane.

The diagram shows a six degree of freedom model (6 DOF) of the main aircraft. Two main landing gears, each with two wheels are shown. The number of main landing gears and wheels per landing gear may vary considerably. The degrees of freedom are:

x Longitudinal position of the aircraft center of gravity along the runway centerline

y Lateral position of the aircraft center of gravity relative to the runway centerline

z Vertical distance of the aircraft center of gravity from the ground plane

θ Aircraft pitch angle

ϕ Aircraft roll angle

ψ Aircraft yaw angle

The aerodynamic forces and moments are (about an aerodynamic reference point):

F_L Lift

F_D Drag

F_Y Lateral aerodynamic force (crosswind, rudder, etc.)

M_P Aerodynamic pitch moment

M_R Aerodynamic roll moment

M_Y Aerodynamic yaw moment

Other forces and moments are (gear forces and moments are about the gear attach points):

W Aircraft weight

F_T Total thrust

F_{T1} Thrust, engine 1

F_{T2} Thrust, engine 2

F_{zg} Total vertical force transmitted from the main gears to the aircraft body

F_{zgr} Vertical force transmitted from the right main gear to the aircraft body

F_{zgl} Vertical force transmitted from the left main gear to the aircraft body

F_{xg} Total aftward directed forces transmitted from the main gears to the aircraft body

F_{xgr} Aftward directed force transmitted from the right main gear to the aircraft body

F_{xgl} Aftward directed force transmitted from the left main gear to the aircraft body

F_N Vertical force transmitted from the nose gear to the aircraft body

M_{yg} Total pitch moment transmitted from the main gears to the aircraft body

Although the diagram does not show the main gears generating lateral forces, roll moments, or yaw moments, high fidelity gear, and wheel/tire models could certainly do so.

The minimum aircraft body degrees of freedom necessary for antiskid system simulation and tuning is three: forward motion, vertical motion, and pitch.

Adding the roll degree of freedom allows better evaluation of the effect on antiskid of crosswind and other inputs that may excite the roll mode, such as a rough runway. Adding the lateral and yaw degrees of freedom allows better evaluation of antiskid's interaction with directional control. However, adding the ability to steer the airplane in the simulation means that the pilot's contribution to steering must, in some way, be simulated. The simulation of nose wheel steering and rudder steering might also be problematic.

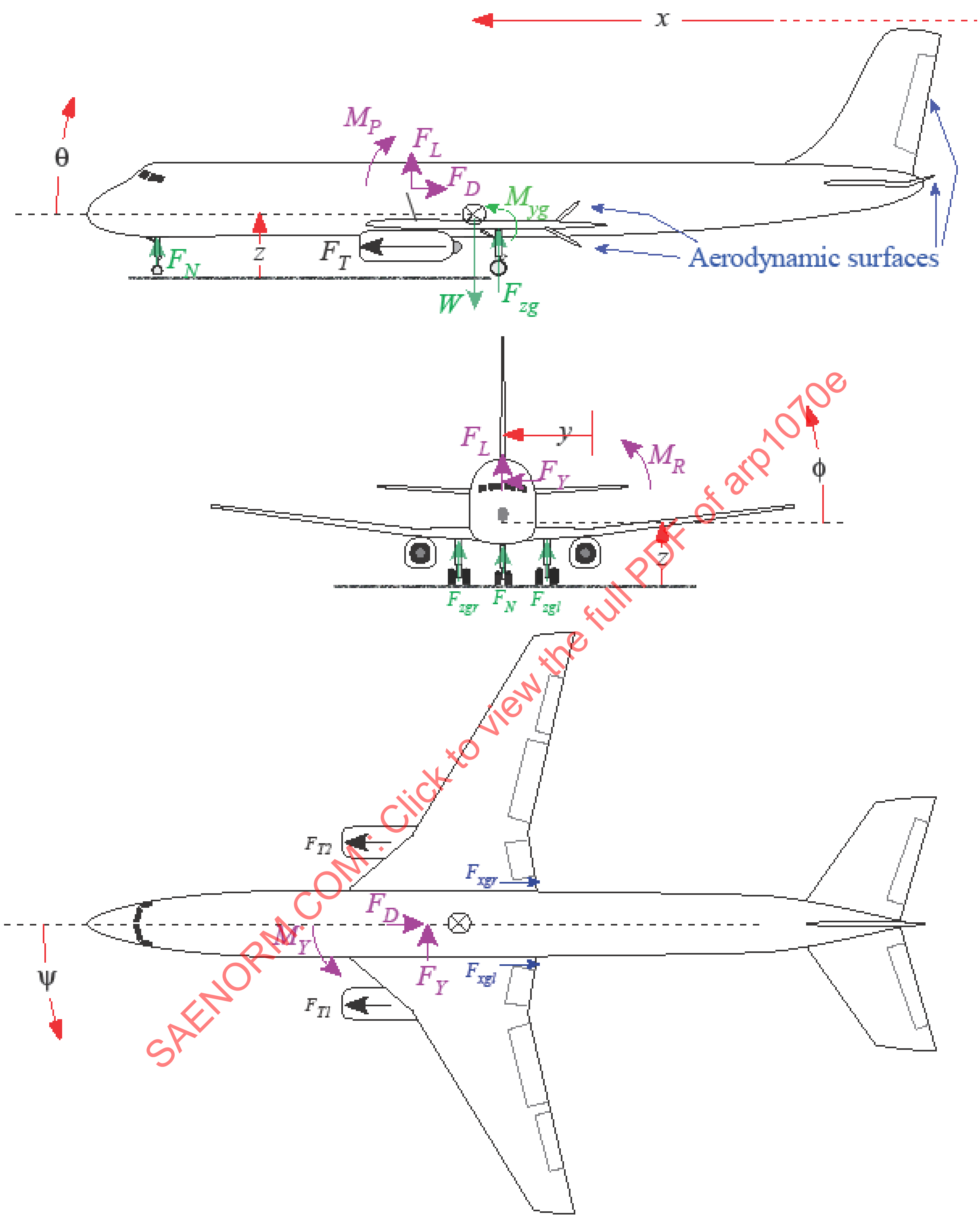

Figure 21 - Airplane free body diagram