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

RATIONALE

This document has been reaffirmed to comply with the SAE 5-year Review policy.

TABLE OF CONTENTS

1. SCOPE 3

1.1 Purpose 3

2. APPLICABLE DOCUMENTS..3

2.1 SAE Publications 3
2.2 Military Publications 3
2.3 Other Publications 4

3. GENERAL REQUIREMENTS..5

3.1 Introduction 5
3.2 Design Practices 6
3.3 Design Goals 13

4. PERFORMANCE TESTING AND EVALUATION 18

4.1 Component Tests 18
4.2 System Level Tests 19
4.3 Aircraft Tests..26

5. CONFIGURATION/INSTALLATION 33

5.1 Configuration Considerations 33
5.2 Wheel Speed Sensors, Number, Arrangement and Location 34
5.3 Skid Control Valves, Number, Arrangement and Location 34
5.4 Control Box Configuration and Location 35

TABLE OF CONTENTS (Continued)

6. LESSONS LEARNED 35

6.1 Skid Control System 35
6.2 Tire Dynamics 36
6.3 Computer Simulation 36
6.4 Special Feature/Considerations 36
6.5 On/Off Switch 36

FIGURE 1 Tire Braking and Side Force Relationship with Wheel Slip 7
FIGURE 2 Typical Relationship Between Drag and Side Friction to Wheel Skip Ratio 10
FIGURE 3 Brake Control Simulator 21
FIGURE 4 Computer Simulation Model 22

TABLE 1 Factors Influencing Stopping Performance 8
TABLE 2 Suggested Aircraft Antiskid Test Schedule 27

1. SCOPE:

This document covers the general requirements for aircraft skid control systems and their components.

Methods of defining skid control system performance criteria for design and evaluation purposes are outlined and recommended.

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, are covered in detail.

Recommended methods for measuring performance of a skid control system are included.

1.1 Purpose:

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

2. APPLICABLE DOCUMENTS:

The following publications form a part of this specification to the extent specified herein. The latest issue of SAE publications shall apply.

2.1 SAE Publications:

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

AS483	Skid Control Equipment
AIR764	Skid Control System Vibration Survey
ARP862	Skid Control Performance Evaluation
AIR1064	Brake Dynamics
AIR4004	Guide for Installation of Electrical Wire and Cable on Aircraft Landing Gear

2.2 Military Publications:

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

MIL-S-4040	Solenoid, Electrical, General Specification for
MIL-W-5013	Wheel & Brake Assemblies, Aircraft
MIL-W-5088	Wiring Aircraft Selection & Installation
MIL-E-5400	Electronic Equipment Airborne General Specification for
MIL-V-5529	Valve, Hydraulic Directional Control
MIL-V-7915	Valves, Hydraulic, Directional Control, Slide Selector

2.2 (Continued):

MIL-H-8775	Hydraulic System Components, Aircraft and Missiles, General Specification for
MIL-H-8891	Hydraulic Systems, Manned Flight Vehicles, Type III Design, Installation & Data Requirements for (ASG)
MIL-B-8075	Brake Control Systems, Antiskid, Aircraft Wheels, General Specification for
MIL-B-8584	Brake Systems, Wheel, Aircraft, Design of
MIL-C-83723	Connectors, Electrical, Circular, Environmental Resisting
MIL-L-87139	Landing Gear Systems
MIL-STD-100	Engineering Drawing Practices
MIL-STD-143	Standards & Specifications Order of Precedence for the Selection of
MIL-STD-461	Electromagnetic Interference Characteristics Requirements for Equipment
MIL-STD-470	Maintainability Program Requirements (for Systems & Equipment)
MIL-STD-471	Maintainability Demonstration
MIL-STD-704	Electric Power, Aircraft, Characteristics & Utilization of
MIL-STD-785	Reliability Program for Systems & Equipment Development & Production
MIL-STD-790	Reliability Assurance Program for Electronic Parts Specifications
MIL-STD-810	Environmental Test Methods
MIL-STD-882	Systems Safety Program for Systems & Associated Subsystems & Equipment, Requirements for
DOD-STD-21671	Dept. of Defense System Software Development

2.3 Other Publications:

TP-1051	NASA, Behavior of Aircraft Antiskid Braking Systems on Dry and Wet Runway Surfaces (Slip-Velocity-Controlled)
TN D-4602	NASA, Investigation of the Effect of Wheel Braking on Side-Force Capability of a Pneumatic Tire
TN D-8202	NASA, Some Effects of Adverse Weather Conditions on Performance of Airplane Antiskid Braking Systems
TN D-8332	NASA, Behavior of Aircraft Antiskid Braking Systems on Dry and Wet Runway Surfaces (Velocity-Rate-Controlled)
TN D-8455	NASA, Behavior of Aircraft Antiskid Braking Systems on Dry and Wet Runway Surfaces (Slip-Ratio-Controlled)
TP-1959	NASA, Dynamics of Aircraft Antiskid Braking Systems, 1982
TN D-8252	Friction Characteristics of 20 X 4.4 Type VII Aircraft Tires Constructed with Different Tread Rubber Compounds, July 1976

3. GENERAL REQUIREMENTS:

3.1 Introduction:

The skid control 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 pressure at all times to generate the brake torque such that the tire-runway friction force is maintained close to its peak value, and thus give the aircraft maximum available deceleration which results in the shortest possible stop distance. The performance of the skid control system is dependent upon the degree of compatibility achieved between the skid control equipment, the airplane's landing gear and airframe, and the remainder of the brake control system.

3.1.1 Functional Operation: In operation, the pilot commands pressure to the brakes in proportion to the pilot's brake pedal force and/or pedal travel. If there are no incipient skids, the skid control system does not interfere with the pilot input. If there are incipient skids, the skid control system overrides the pilot's input and reduces the brake pressure by venting (dumping) to hydraulic return 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.

The skid control system controls the brake pressure through a skid control valve 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 valve to release the brake pressure. Upon command from the controller, the skid control valve reduces brake pressure by releasing the fluid from the brake to the hydraulic system return. When the wheel spins up, the controller reapplies brake pressure at a controlled rate through the skid control valve until another incipient skid occurs or commanded pressure is achieved.

3.1.2 Performance: The skid control 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, and should have provisions for releasing an inadvertently locked brake within the control speed range. For maximum efficiency, brake pressure should be reduced by the smallest amount necessary and for the shortest time possible. Specific areas that need to be addresses are:

a. Rapid initial adjustment to the optimum control pressure
b. Operation at partial metered pressures
c. Rapid adjustment to changing runway conditions
d. Control of high onset brake pressure (spikes)

The skid control system should not induce or be adversely affected by airframe dynamic instabilities such as gear walk, truck pitch, gear shimmy, brake chatter, brake oscillations, etc., throughout the full aircraft ground operation spectrum.

3.1.2 (Continued):

The system should be tuned for optimum braking performance over a broad range of operational conditions, including a variety of runways such as dry, wet, icy, etc., throughout the control speed range. The impact of loss of cornering during maximum braking should be addressed. Since the total braking function involves more than the skid control system and wheel, brake and tire assemblies, determination of the total airplane stopping performance is the responsibility of the airframe manufacturer. Where possible, qualified performance should be specified in terms of efficiency or stop distance.

3.2 Design Practices:

3.2.1 Considerations: Advanced landing gear systems contain elastic structure that can cause antiskid stability and performance problems. Current design trends emphasize reduced weight and volume for wheels and brakes, increased shock strut flexibility arising from the use of high heat treated steels, and the use of more responsive skid control braking systems.

In general, brake linings capable of withstanding high rates of energy input, high temperatures, and exhibiting low wear rates have friction variations that can excite landing gear system natural frequencies.

The performance of the skid control system is dependent upon its mutual compatibility with the response characteristics of the aircraft brake system and associated structures; therefore, the designer should consider these and other variables as noted in Table 1 herein.

Poor brake control can degrade the inherent directional stability of the aircraft. Both stopping ability and directional control are dependent upon available friction (mu) between the tire and runway. Current skid controls systems utilize some means to sense the skid level, such as wheel slip (difference between the actual wheel speed and free rolling wheel speed) and modulate the brake pressure to minimize this skid. A typical tire braking force (friction) wheel slip characteristic is shown in Figure 1. With increasing brake pressure, the tire is forced into an incipient skid which allows the tire to traverse onto the "back side" of the mu-slip curve.

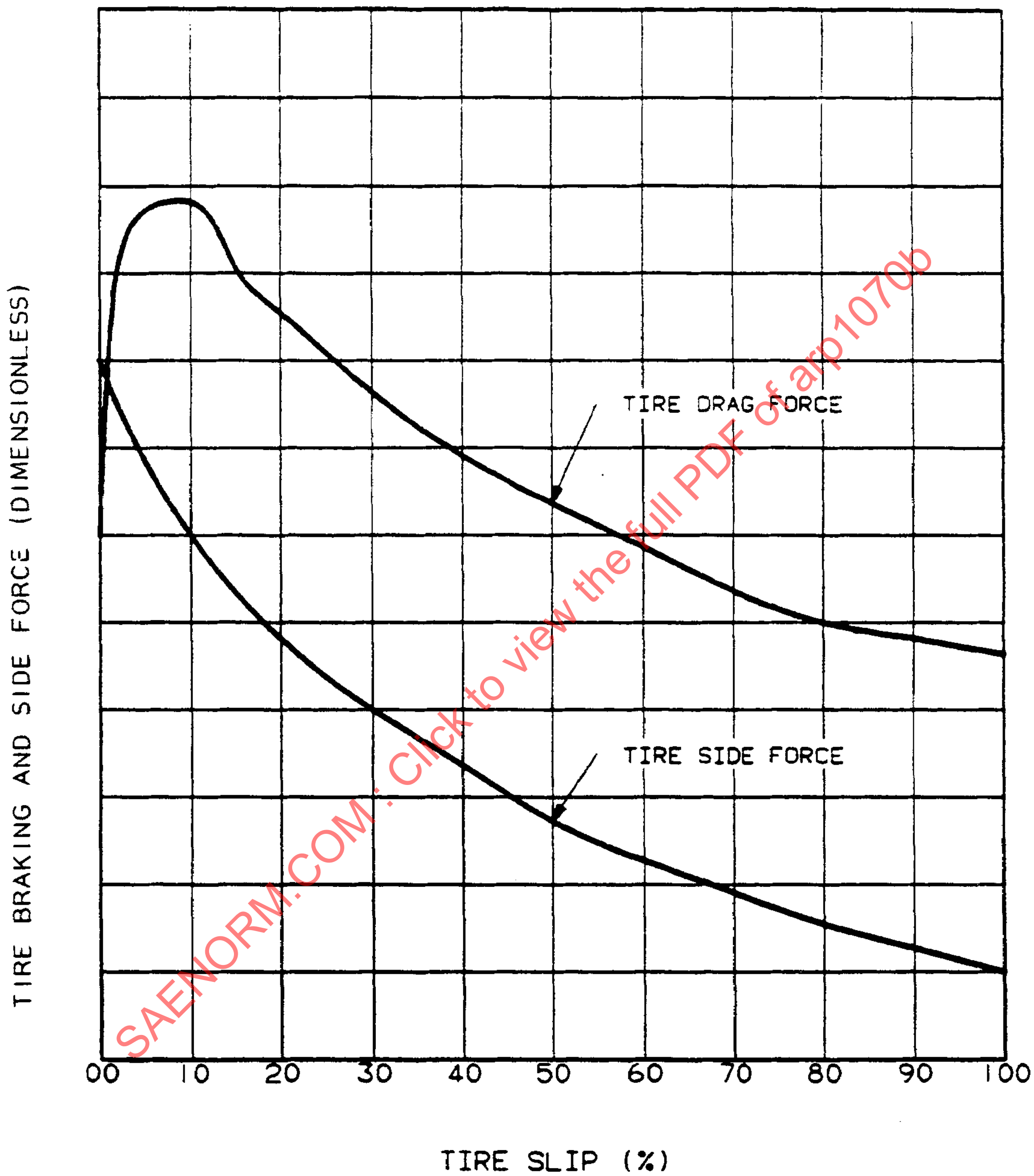


FIGURE 1 - Tire Braking and Side Force Relationship with Wheel Slip
(For Tire Being Rolled at a Fixed Yaw Angle)

TABLE 1 - Factors Influencing Stopping Performance

Subsystem Parameters

Brake Actuation System
- Pedal Linkage to Metering Valves
  - Actuation mechanism mechanical advantage
  - Cable length and stiffness
  - Pedal force vs pressure characteristics
- Hydraulics
  - Hydraulic pump capacity and recovery rate
  - Accumulator pressure/volume characteristic
  - Fluid type
  - Brake line length, size and stiffness
  - Component flow restrictions
  - Return line back pressure (steady state and transient)
  - Metering valve flow capacity
  - Metering valve pressure gain
  - Hydraulic system response

Antiskid System
- Wheel Speed Detector
  - Speed sensor drive mechanism
  - Electrical characteristics
  - Resolution
  - Demodulator characteristics
- Electronics
  - Skid control logic
  - Response characteristics
- Servovalve
  - Flow gain
  - Pressure gain
  - Second stage lap
  - Frequency response

Wheel, Brake, and Tire System
- Brake
  - Pressure-volume characteristics
  - Lining characteristics
  - Heat sink loading
  - Torque onset
  - Torque release
  - Application time (autobrake or not)
  - Heat transfer characteristics
  - Retractor spring pressure
  - Wear adjusters
  - Brake mounting stiffness
  - Vibration characteristics
  - Torque-temp-speed-pressure characteristics
  - Torque pressure hysterisis
  - Internal hydraulic damping
- Tire
  - Footprint area
  - Inflation pressure
  - Type (radial vs bias ply)
  - Fore and aft stiffness
  - Vertical stiffness
  - Lateral stiffness
  - Mass
  - Inertia
  - Treat design and wear
  - Thermal properties
  - Rolling resistance
  - Diameter
  - Damping characteristic
  - Nose wheel tire size (when used as velocity reference)
  - Friction characteristics

Airplane
- Aerodynamics/Propulsion
  - Brakes-on speed
  - Aerodynamic coefficients (lift and drag)
  - Spoiler deployment rate and effectiveness
  - Engine idle spindown and reverse thrust characteristics

Related Aircraft System Parameters

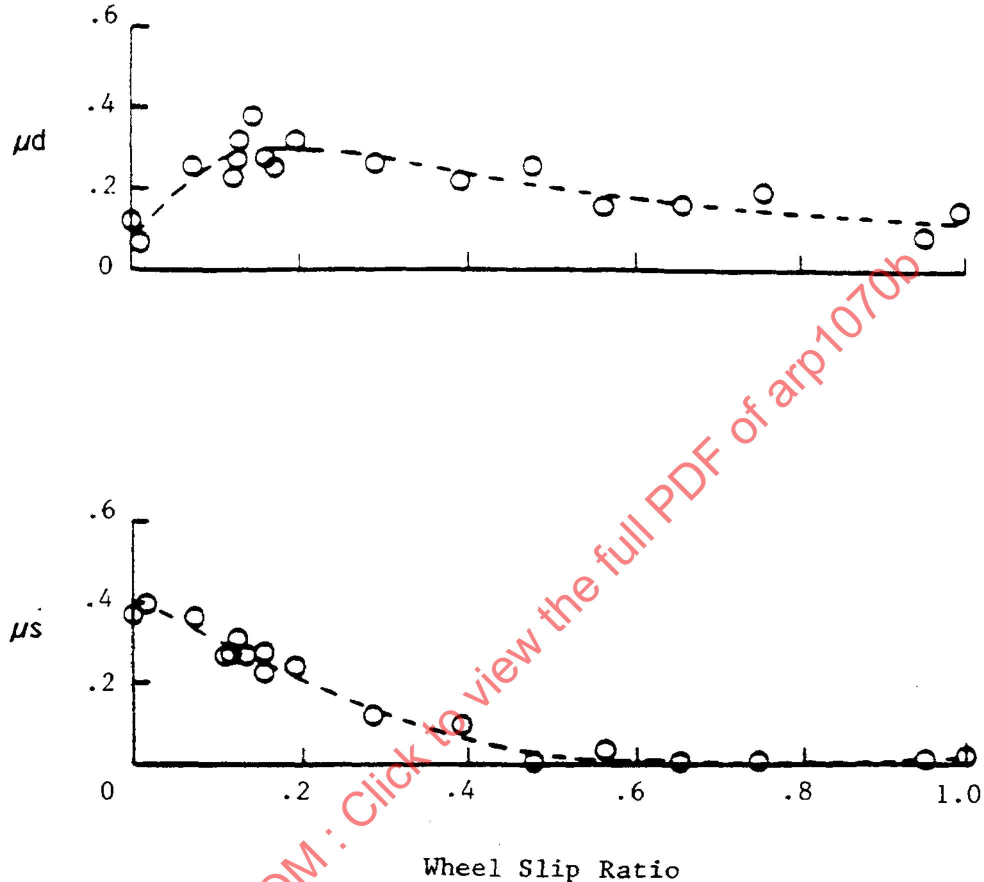
Landing Gear
- Strut
  - Fore and aft stiffness
  - Strut effective mass
  - Fore and aft damping
  - Vertical stiffness
  - Metering pin design
  - Torsional stiffness
  - Torsional damping
  - Strut geometry
  - Metering characteristics
- Truck
  - Mass
  - Truck unbalance
  - Truck pitch dynamics

TABLE 1 (Continued)

Directional Control
Nose gear steering system
Aircraft control surfaces
Differential braking
Geometry/Configuration
Center-of-gravity location
Landing gear arrangement
Airplane weight
Airplane mass moment of inertia
Wing stiffness
Operational Characteristics
Pilot landing and braking technique
Environmental Parameters
Runway
Roughness (Micro and Macro Texture)
Contamination (water, rubber deposits)
Slope
Crown
Groove Pattern
Atmospheric
Ambient Temperature
Pressure Altitude
Wind Velocity and Direction

3.2.1 (Continued):

Measured values (refer to Figure 2) indicate that the side force is reduced on the "back side" of the curve. Therefore, it is most advantageous to specify brake control systems that dwell predominantly in the upper regions on the "front side" of the curve. Skid control system optimization to obtain best stopping performance should also ensure high lateral force capability. This can best be accomplished by system "tuning". The least expensive method to accomplish this tuning is through the use of an analog or digital skid control simulator that enables assessment of the period of time the system dwells on the back side of the mu-slip curve. The simulator can also be used to assess the effects of failure modes on system performance. Although data gained through this method are valuable in determining a measure of directional control stability for the aircraft, the total ground control problem is much more complex and consideration must be given to all aircraft related influences that combine to produce satisfactory stopping performance. Man-in-loop flight simulator tests may be conducted to assess aircraft yaw and pitch stability under various runway conditions, and to evaluate different methods of wheel control (single versus paired wheel). Final resolution should be achieved during actual aircraft evaluation.



Variation of computed friction coefficients with wheel slip ratio during brake cycle on dry concrete. Yaw angle, 10.9°; ground speed, 106 knots. (NASA data, 20 x 4.4 Type VII Aircraft Tire TN D-8252). μd and μs are friction coefficients of drag and side force respectively.

FIGURE 2 - Typical Relationship Between Drag and Side Friction to Wheel Slip Ratio (For Tire Being Rolled at a Fixed Yaw Angle)

3.2.2 Skid Control System Responses: A primary design objective is the attainment of minimum response time in each of the skid control components involved in the completion of a skid control cycle. Nevertheless, this objective should be compatible with the elastic characteristics of the landing gear, airframe, tire, brake, and hydraulic system. A skid control cycle consists of the following events:

a. Measure of excessive wheel deceleration or tire slip
b. Reduction of brake pressure at skid control system command to minimize tire skid
c. Reapplication of brake pressure to achieve the airplane deceleration commanded by the pilot or the maximum attainable, whichever is less

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. Skid control system response characteristics
b. Brake assembly response characteristics
c. Hydraulic system response characteristics
d. Airplane gross weight and moments of inertia
e. The elastic and damping characteristics of the landing gear, high drag and torsional loads at low speeds, and strut compression may affect the structure
f. Airplane aerodynamic characteristics
g. Tire to runway friction for various tire tread and runway conditions
h. The brake's pressure versus torque characteristics and variations in brake frictional coefficients result from different energy levels
i. Brake system command pressure characteristics
j. Elastic (stiffness) and damping characteristics of the tires
k. Aircraft directional response and characteristics
l. Landing gear natural frequency (fore/aft, torsional)

3.2.3 Recommended Data Exchange: Technical data required for design and analysis should be completed in specification or formally agreed to technical data exchanges to assure the least amount of system deficiencies prior to aircraft test. Therefore, the following data exchanges are recommended:

3.2.3.1 Airframe Manufacturer Supplied Data: The airframe manufacturer should supply the following data to the skid control manufacturer:

a. Aircraft Parameters:

(1) Aircraft Weight

(a) Maximum takeoff
(b) Design landing
(c) Aircraft weight empty

3.2.3.1 (Continued):

(2) Aircraft velocity at brake application - maximum takeoff weight, normal and lightweight landing
(3) Distance from ground to CG - maximum takeoff weight, normal and lightweight landing
(4) Distance from nose gear to main gear
(5) Distance from nose gear to CG
(6) Mass moment of inertia about CG - maximum takeoff weight, normal and lightweight landing
(7) Aerodynamic lift coefficient (takeoff and landing configuration)
(8) Aerodynamic drag coefficient, (takeoff and landing configuration)
(9) Idle thrust, and engine thrust decay characteristics
(10) Weight of one main landing gear
(11) Number of wheels per main landing gear
(12) Vertical spring rate. Main gear and nose gear
(13) Vertical damping rate. Main gear and nose gear (send characteristic curves if available)
(14) Distance from ground to CG with extended main gear
(15) Main gear drag stiffness
(16) Main gear fore-aft natural frequency
(17) Main gear fore-aft damping ratio (percent of critical)
(18) Main gear torsional stiffness
(19) Distance between main gears
(20) Distance from center of axle centerline to center of gear

b. Brake System Hydraulic Plumbing:

(1) Line length, size and type of supply line, brake line, and return line - location of brake metering valve and location and size of accumulators - location and size of significant restrictors such as a swivel - hydraulic system schematic
(2) Brake metering valve pressure-flow characteristics
(3) Hydraulic supply pressure-flow characteristics
(4) Brake pressure available
(5) Supply pressure maximum and metered pressure

c. Brake Parameters:

(1) Lining contact pressure (psi)
(2) Pressure-volume characteristics
(3) Torque-pressure characteristics including range of friction coefficients
(4) Torque-speed characteristics
(5) Weight of brake
(6) Moment of inertia of brake rotors
(7) Axle dimensions (for wheel speed transducer)
(8) Frequency response, torque/pressure

3.2.3.1 (Continued):

d. Tire Parameters, Main Landing Gear:

(1) Tire size and type
(2) Fore-aft spring rate
(3) Vertical spring rate
(4) Tire weight
(5) Normal tire pressure and rolling radius
(6) Wheel weight
(7) Tire peak mu versus velocity if available
(8) Moment of Inertia of tire and wheel

e. Miscellaneous:

(1) Skid control system schematics, envelope, and mounting requirements
(2) Maximum and minimum speeds for which skid control must be operational
(3) Skid control system efficiency requirements
(4) Designation of special features such as touchdown protection, locked wheel protection, or automatic braking feature
(5) Description of the control and warning devices to be provided for the pilot
(6) Electromagnetic interference (EMI) and environmental requirements

3.2.3.2 Skid Control Manufacturer Supplied Data: The skid control manufacturer should provide the following to the airframe manufacturer:

(a) Electronic schematics
(b) Failure modes and effects analysis
(c) Reports showing compliance with specified requirements - detail design analysis by component and as a system
(d) Skid control system component characteristics as required by the customer for overall brake system analysis
(e) Recommended system maintenance and checkout procedures
(f) Recommended ground support equipment
(g) Control algorithm description
(h) Complete working drawings, including proprietary data appropriately marked
(i) Unit acceptance test procedures including substantiation of testing requirements
(j) Qualification test procedure and test results
(k) System safety evaluation
(l) Reliability predictions

3.3 Design Goals:

The following are recommended design goals for the skid control system.

3.3.1 System Function: The system should prevent wheel lockup under normal operating conditions including dry, wet, and icy runway.

3.3.2 System Efficiency: The system should provide braking efficiencies in the order of 90% or better, as defined in 4.2.2.4 herein or in MIL-B-8075.

3.3.3 Operating Range: The system should operate near the peak of the braking force-slip curve in order to maximize energy transfer to the brake and minimize energy transfer to the tire. It is necessary to minimize excursions to the backside of the mu-slip curve to prevent excessive tire wear and tire heating which limits the tire's braking capability. The development of maximum braking force requires that the "runway be tested" with slip excursions to the back side to confirm that maximum braking is being developed. The skid control should operate most of the time in as narrow a slip range as possible at the peak of the braking force curve.

3.3.3.1 Environmental Consideration: The components should be designed and verified for the full range of anticipated environmental conditions. These must include:

a. Temperature
b. Humidity
c. Vibration
d. Acceleration
e. Shock
f. EMI

3.3.4 Braking Versus Cornering Interaction: The system should operate in such a manner as to maintain tire cornering capability as high as possible. This can be accomplished by maintaining operation of the skid control system in a narrow range near the peak of the braking force curve.

3.3.5 Pilot Controllability: The skid control system should not impair the pilot's ability to apply and release the brakes or adversely impact the controllability of the aircraft.

3.3.6 Landing Gear and Airframe Structural Loads: The skid control system should not impart 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.

3.3.7 Software: 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 autobrake system. The detected faults should be isolated to a replaceable unit. A software management and discipline must be employed to ensure control of configuration and proper validation.

3.3.8 Brake Application Response: The skid control system should not reduce the brake control system's ability to respond to the pilot's commands. However, if the addition of a skid control system to the aircraft should cause a significant change in the brake control system's ability to respond to rapid changes in pilot command, an analysis should be performed to show that this change does not adversely affect landing gear dynamic loads or introduce any undesirable airplane pitching characteristics.

3.3.9 Hydraulic System Design Goals and Considerations:

3.3.9.1 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 the skid control valve in the application and release of brake pressure associated with skid control.

3.3.9.2 Hydraulic Lines: Hydraulic lines and fittings should be designed to minimize restriction of flow with the objective of optimizing skid control response time. However, restrictor check valves may be used when needed to provide additional damping.

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 overpressurized 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.

3.3.9.3 Internal Leakage of the Skid Control Valve: Internal leakage of the skid control valve should be minimized (to the extent valve performance is not compromised) in installations where it is necessary to reduce the bleed-off of any accumulator pressure which is available for parking or as a stored passive emergency supply. However, consideration should be given to any reduction in valve performance that may result from reduced internal leakage.

3.3.9.4 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.

3.3.9.5 Fly-By-Wire Brake and Antiskid System: With a fly-by-wire brake and antiskid control system the brake metering valve and antiskid control valve can be incorporated into a single hydraulic brake module assembly. The brake pedal mechanism to the brake metering valve can be replaced with a brake pedal feel mechanism and brake pedal transducers. The brake pedal transducers send brake command signals to the antiskid control unit, which in turn commands the hydraulic brake module assembly to apply brake pressure.

3.3.10 Brake Design Goals and Considerations:

3.3.10.1 Response: Minimum brake response time is desirable. The airframe manufacturer should determine and provide brake response time data to the skid control system manufacturer such as step response and frequency response between brake pressure and torque. This data should be a part of brake design requirement.

3.3.10.2 Pressure: Maximum aircraft hydraulic system pressure should be specified for maximum metered brake operating pressure whenever practicable.

One case that does not use maximum hydraulic system pressure is the situation where it is desired to use accumulator pressure in the hydraulic system for emergency braking. In this case, a lower brake operating pressure is required to allow a maximum number of brake applications. Another case might be the use of dual brake pressure control systems, where loss of one system is compensated by an increase in maximum output pressure from the other system.

3.3.10.3 Fluid Displacement: 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 skid control system should be confirmed). A relatively high brake structural spring rate and self-adjusters should be considered to accomplish the above.

3.3.10.4 Fluid Passages: 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 provide additional damping to minimize brake vibrations. For example, damping for the brake whirl mode of vibration is frequently achieved by brake passage restrictions.

3.3.10.5 Mechanisms: Brake release mechanism, 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.

3.3.10.6 Seals: The brake hydraulic seals should be adequately protected against entry of foreign material within the expected environment.

3.3.10.7 Port Location: The brake pressure ports should be located at the top to allow self-bleeding.

3.3.10.8 Reaction Torque: The brake's torque should be reacted in such a manner that brake applications do not result in variations of the vertical wheel loads.

3.3.10.9 Return Springs: Return springs should be strong enough to overcome brake piston seal friction and reservoir pressure plus additional force for satisfactory brake-off response. Consideration should be given to return line surge pressures.

3.3.11 Electrical Design Goals and Consideration:

3.3.11.1 Electrical Power: The following items should be considered in regard to electrical power design for the skid control system:

a. Normal and emergency power characteristics should be evaluated for any detrimental effect on system performance.

b. A means to engage or disengage electrical power should be made available to the pilot.

c. Voltage transient protection should be incorporated in all electrical and electronic assemblies.

d. Power interruption characteristics should be evaluated and criteria established for skid control performance.

e. Power redundancy or isolation should be utilized to minimize total system failures.

3.3.11.2 Electromagnetic Interference (EMI): Consideration should be given to EMI design requirements sufficiently early in a skid control system design program to preclude operational problems on the aircraft.

EMI tests should be performed on the skid control 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 strike on the strut.

3.3.11.3 Wiring: Wire routing should be controlled to prevent interaction between the skid control system and other equipment.

It is generally considered good design practice not to use wire smaller than AWG number 22 gage.

Shielded wire should be considered for sensitive circuits such as the wheel speed sensing circuit. It is recommended that the shield be continuous and grounded at both the sensor and the control box connector.

3.3.11.4 Connectors: Connectors should be environment resisting type. In high vibration areas, such as the landing gear, the connectors should be the threaded type with lock wire. The large 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 boxes, etc.), positive means to prevent misconnection such as different shell size, wire routing, or clocking connectors should be considered.

3.3.11.5 Environmental Stress Screening: Components should be capable of successfully completing environmental stress screening tests as part of the acceptance test program.

3.3.11.6 Temperature Effects: The components should be suitable for operation in the anticipated temperature environment and then reassessed after performance on the aircraft. Particular attention should be given to the cold temperature effect on servovalve response and the resultant effect on performance.

4. PERFORMANCE TESTING AND EVALUATION:

Performance testing and evaluation of the skid control system and associated equipment can be separated into two categories:

a. Component tests
b. System level tests

4.1 Component Tests:

Testing of individual components of the skid control 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.

4.1.1 Brake Tests: Dynamometer testing of brakes is essential to the evaluation of the skid control system. Test data from landing energy and overload energy stops help determine the brake torque- pressure characteristics, the effect of temperature and velocity on the values of developed torque, and other nonlinear effects that need to be accounted for in the skid control system tuning.

4.1.2 Tire Tests: Static and dynamic data from tire tests are essential for evaluation of the total system performance. Typical required data include:

a. Vertical load deflection data
b. Fore and aft stiffness
c. Cornering characteristics
d. Torsion stiffness

4.1.3 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.

4.2 System Level Laboratory Tests:

Total performance laboratory testing and evaluation of a brake control system can be conducted on:

a. Brake control simulators
b. Dynamometer

Brake control simulation testing should be conducted prior to aircraft testing to minimize risk and to tune the antiskid components for the particular aircraft application.

Dynamometer tests should not be considered a substitute for aircraft or computer simulation tests in determining and optimizing overall braking efficiency and effectiveness. Dynamometer testing, while not mandatory during the development cycle of a skid control system, can offer information on potential problem areas.

4.2.1 Brake Control Simulator: Computer simulation testing should be conducted to ascertain the degree of flexibility that exists within the control loop of the skid control system. The minimum variations that should be explored are:

a. Gear damping
b. Reduced pressure input
c. Truck pitch
d. Variations in runway mu
e. Brake torque gain

Other variations to be considered include:

a. Step changes in ground coefficient
b. Step changes in applied brake pressure
c. Significant differences in rolling radius (flat tire) on multiwheel gear which have wheel pairing (paired wheel control or locked wheel protection)

4.2.1 (Continued):

Performance testing and evaluation of skid control systems should be conducted on a real time, hardware in loop, brake control simulator. These hybrid simulators are a combination of components, brake hydraulic hardware, antiskid controllers, and associated interface equipment. The characteristics of the aircraft must be simulated accurately to test the controller in a repetitive fashion under a variety of operational conditions.

4.2.1.1 Description: The following is a brief description of the simulators and their operation. Figure 3 illustrates an overall schematic.

a. Computers: The computers are used to simulate the aircraft dynamic characteristics. These include mathematical models for the airplane, landing gear, wheel, tire, brake dynamics, and tire to ground interface. Until recently, these simulations have been done using all analog or hybrid (analog/digital) computers. However, the state-of-the-art parallel processing digital computers can now perform all calculations in real time that previously necessitated the use of analog computers. Figure 4 shows a typical schematic of 3 degrees of freedom (longitudinal) aircraft simulation model.

   The laboratory data from the brake dynamometer tests are used to model the dynamic characteristics of the brake to include torque fade, peaking, and other nonlinear effects. The expense and the inability to make frequent repetitive runs precludes the use of the dynamometer as a skid control system tuning/evaluation tool.

b. Computer Simulation Model (Parameters in Figure 4):

   (1) D - Drag due to brake torque
   (2) D_A - Aerodynamic drag
   (3) F_G - Braking drag acting on aircraft mass
   (4) F_M - Vertical load on main gears
   (5) F_N - Vertical load on nose gear
   (6) L - Aerodynamic lift
   (7) P_B - Brake pressure
   (8) T_B - Brake torque
   (9) $\dot{X}$ - Aircraft velocity
   (10) $\dot{X}_G$ - Gear fore-aft velocity
   (11) $\dot{X}_S$ - Tire-runway slip velocity
   (12) $\dot{\theta}_W$ - Wheel angular velocity
   (13) $\dot{Z}$ - Aircraft vertical velocity at CG
   (14) Z - Aircraft vertical displacement at CG
   (15) $\dot{\theta}$ - Pitch rotation velocity
   (16) θ - Pitch rotation
   (17) T_J - Idle thrust

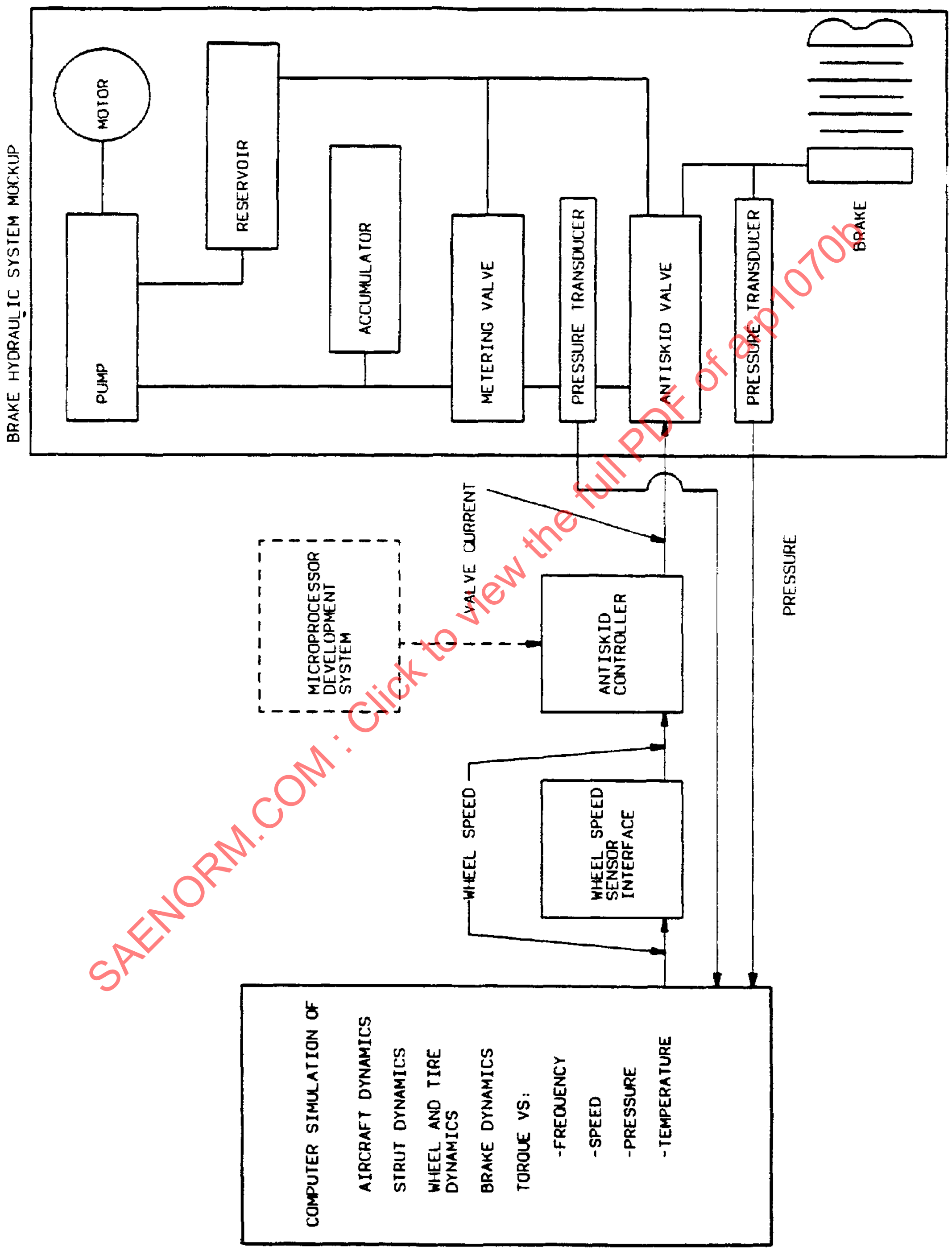


FIGURE 3 - Brake Control Simulator (Typical)

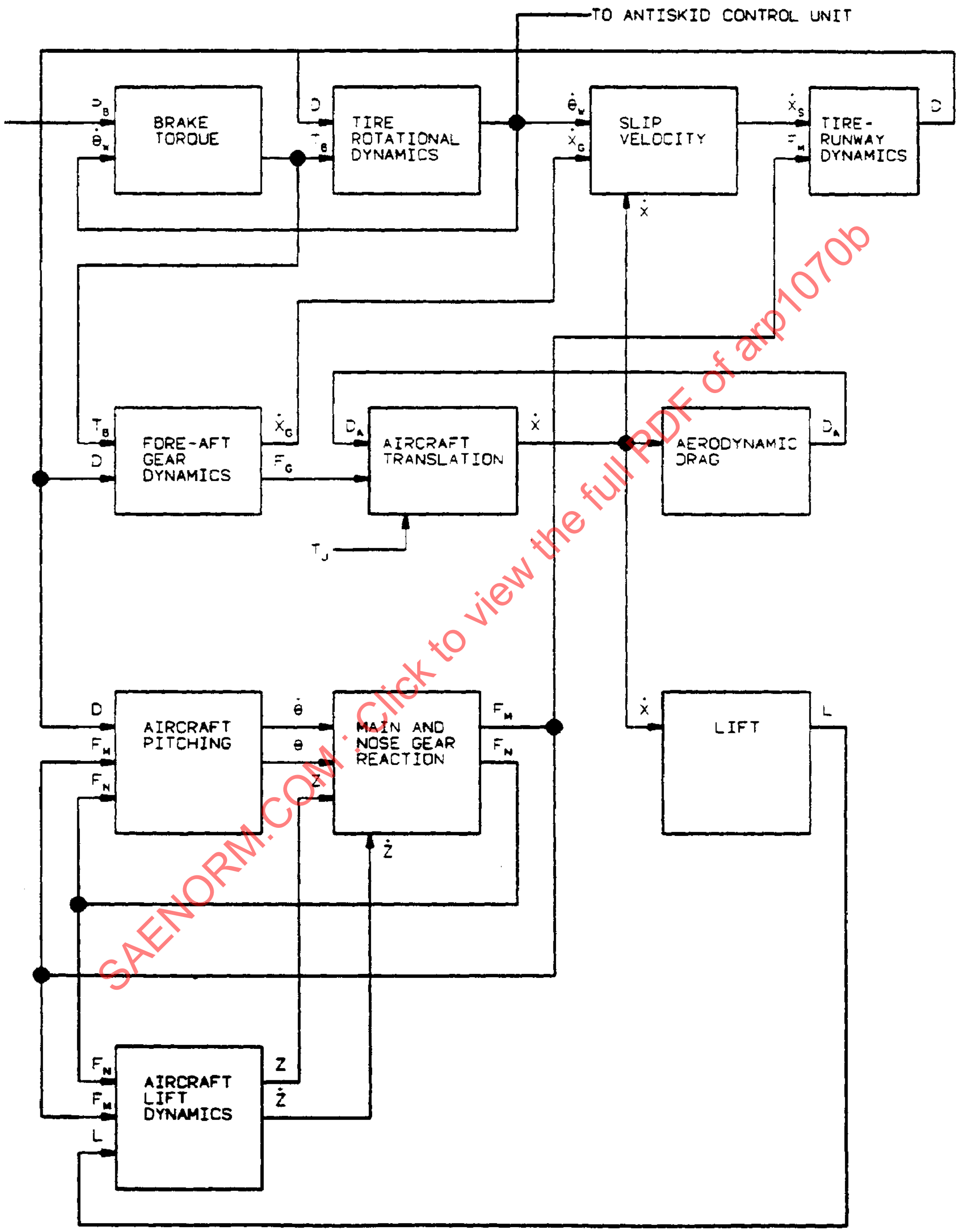


FIGURE 4 - Computer Simulation Model

4.2.1.1 (Continued):

c. Brake Hydraulics: A mockup of the actual hydraulic system is built and used as an integral part of the simulator. This is done to simulate the hydraulic dynamic response of the air vehicle. Typically, this includes all the hydraulic components associated with a brake control system and is unique for each airplane. Use of the following hardware should be considered:

(1) Brake metering valve(s) for one side of the airplane
(2) Nonrotating brake stacks and pistons connected to skid control valves for the brakes on one side of the airplane
(3) Pump, accumulator, reservoir, and other components
(4) Representative lines and hoses between brakes, valves, and components
(5) Skid control valves

The brakes should preferably be actual aircraft brakes, or a hardware simulation having the same pressure-volume characteristics. An objective of the hardware system is to achieve representative brake fill, dump, and transient response characteristics of brake pressure. Brake pressure is measured and interfaced with the computer simulation of brake pressure-torque and wheel-runway interaction. The use of the mockup ensures accurate hydraulic system response and allows detailed antiskid evaluation.

d. Controller: During real time testing, a prototype breadboard or an actual controller is in the simulation loop as shown in Figure 3. 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.

4.2.1.2 Simulator Test: Simulator testing of brake control system hardware permits evaluation in a controlled environment. The computer simulation is tuned to match brake characteristics from dynamometer testing and airplane test data time histories by varying computer parameters. The simulation can then be used for optimizing stopping performance by changing control parameters in the skid control box. Efficiencies and performance parameters can be calculated by comparing computer predictions of drag force, stopping distance, etc., with "perfect stop" reference data. "Perfect stop" reference data is obtained by calculating performance when the maximum available drag force occurs continuously during a stop. Literally thousands of simulated landing rollouts can be made covering a wide variety of operational conditions. These tests are used to optimize the performance of the control systems and ensure good control under both normal and adverse runway/weather conditions. In addition, simulators permit evaluation of the controller under failed/or hazardous conditions that could not be conducted on the airplane because of safety and control limitations.

Typically, testing and tuning of the brake control system should include the following tests:

4.2.1.2.1 System Performance Tests: Stopping distance evaluation for a variety of constant friction conditions MU=0.05 to maximum level expected on the runway.

a. Adaptability: Control system performance to sudden changes in runway friction conditions (wet puddles, icy patches, etc.) and runway roughness (steps, bumps, discontinuity, etc.)

b. Effect of Varying Metered Pressure: Control system performance at various constant metered pressure levels and varying cyclic metered pressures.

c. Family Variations: Stopping distance and system performance for variations in tire sizes, brakes, initial velocity, and landing weights.

d. Dynamic Stability: Determination of the effect of system performance by varying gear fore and aft stiffness and system damping. Investigation of the effect of dynamic variations in wheel speed.

The antiskid should be tuned to provide optimum control and performance under all operational conditions.

Once the airplane is available, flight test and laboratory tests should be done interactively. Problems and inefficiencies observed during flight test should be analyzed and duplicated on the simulator. System tuning parameter changes and control algorithm modifications need to be defined and incorporated in the flight test control unit, and the flight tested again. The cycle is repeated until satisfactory performance is achieved. Besides reducing flight test time, this approach produces state-of-the-art brake control systems, which operate over the entire friction coefficient range with braking efficiencies above 90%.

4.2.1.3 Software Development: 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 checks and failure response checks ensure that BIT monitors the operation status and detects the faults.

Software development should be done in accordance with the design specification. Department of Defense Standard 2167A, DOD System Software Development, is an example of an industry software development standard.

4.2.2 Dynamometer Testing of Skid Control Systems: Dynamometer testing is a valuable tool for evaluating operating behavior and compatibility between the various active elements of the total braking system. Although not mandatory, dynamometer testing can offer information on potential problem areas, such as brake vibration, torque variations, and antiskid initialization.

4.2.2.1 Test Equipment: As a minimum, skid control system components should be mounted in a manner similar to the proposed aircraft installation on a suitable stub axle or landing gear carriage. The test setup should include:

a. Dynamometer
b. Loading mandrel which simulates gear and backup structure spring rates, structural damping, and inertia
c. Wheel, tire, and brake
d. Brake hydraulic system which simulates components, line lengths, and line sizes up through the pilot metering valve
e. Antiskid valve, control unit, and wheel speed transducer

4.2.2.2 Instrumentation: For all tests performed, the following quantities should be recorded with respect to time:

a. Hydraulic pressure at the skid control valve inlet port
b. Hydraulic pressure at the brake inlet port
c. Dynamometer peripheral speed
d. Aircraft wheel speed
e. Skid control valve signal
f. Brake torque as measured at the axle
g. Drag force (ground reaction force) if available
h. Wheel load

4.2.2.3 Procedure: The aircraft wheel radial load should be applied by a loading mechanism which maintains the desired vertical load during braking.

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

Both lift and weight transfer effects (due to deceleration) should be taken into account. However, weight transfer may be computed on the assumption that the aircraft nose wheel suspension is infinitely stiff.

4.2.2.4 Efficiency Determination: No accurate method exists to determine antiskid performance from dynamometer tests. The primary function of the dynamometer test should be the determination of system control loop compatibility when this cannot be accomplished on the aircraft. Simulator testing is the preferred method of determining system performance. If simulator and/or aircraft tests are not available, an indication of system performance can be obtained using the following method.

Dynamometer braking efficiency can be estimated by utilizing data obtained from representative dynamometer runs. The drag brace force, brake torque, or brake pressure curves should be integrated from "brakes on" to 10 mph at a minimum of four representative sections to get the actual area under the curves. The peaks (not transients) of the curves may be connected and integrated to get the optimum area. The efficiency of braking is defined as the ratio of the actual area to the optimum area.

A better approximation can be made by using a velocity weighted summation. This is done by multiplying both measured and peak values of torque by velocity before the integration is performed.

4.3 Aircraft Tests:

4.3.1 Test Description: Aircraft testing is the final proof of system adequacy as far as system stability and performance are concerned. Therefore, certain minimum aircraft testing is required to demonstrate design goals and system requirements. A suggested general aircraft flight test schedule is presented in Table 2. More or less testing may be required depending on the aircraft's intended usage, confidence in computer simulation results, and previous airplane tests on similar models. If the skid control system contains entirely new or unproven circuits, consideration should be given to having variable parameters (gains, time constants, etc.) available for expeditious tuning of the system to match the airframe. Also, very early in the aircraft test program, relatively high (80% and up to expected maximum) kinetic energies should be investigated, as this is an area where landing gear component/skid control system instability phenomenon is most likely to occur.

TABLE 2 - Suggested Aircraft Antiskid Test Schedule

Test No.: 1

Test: Skid Control Operation

G.W.: N/A

C.G.: N/A

True Airspeed, Knots: Not moving

Gear: Down

Flaps and Spoiler: N/A

Description of Test: Conduct skid control functional checkout with airplane on the ground

Required Data:

1. Skid control valve voltage signal (LH and RH).
2. Wheel speed voltage signal (LH and RH).
3. Brake pressures (LH and RH).
4. Skid control valve inlet pressures (LH and RH).
5. Return pressure from antiskid valve.

Presentation of Data:

1. Data to be used for verification of correct skid control operation.

Technical Notes - Special Instructions:

1. The system should be checked out per installation and functional test procedure.

2. This test may be used as a checkout for flight test instrumentation.

TABLE 2 (Continued)

Test No.: 2

Test: Skid Control and Brake System Operation (Taxi Tests)

G.W.: Minimum to medium weight

C.G.: Forward

True Airspeed, Knots: Noted

Gear: Down

Flaps and Spoiler: Landing configuration
Rejected takeoff configuration

Description of Test:

1. Perform slow speed (40 KTS) taxi check with skid control on and off for pilot reaction to brake response
2. Apply maximum brake effort with skid control "ON" at 60 knots
3. Conduct high speed taxi runs with skid control "ON"

Required Data: Same as test number 1 plus:

6. Brake torque
7. Aircraft speed
8. Drag strut load
9. Aircraft longitudinal deceleration
10. Brake temperature
11. Axle Temperature
12. Aircraft ground distance travelled (on aircraft equipment)

Presentation of Data:

1. Time histories of the following:
   - Brake pressures
   - Skid control valve inlet pressures
   - Brake temperature
   - Axle temperature
   - C.G. longitudinal acceleration
   - System hydraulic pressure
   - Brake torque
   - Aircraft deceleration and velocity
   - Wheel speeds

Technical Notes-Special Instructions:

1. Various electrical signals to be used for correlation and troubleshooting.
2. Engine thrust level should be noted.