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STATUS OF RECENT AIRCRAFT BRAKING AND CORNERING RESEARCH

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SUMMARY

In an effort to enhance the safety of aircraft antiskid braking and steering systems under adverse weather conditions, NASA Langley Research Center is currently conducting two parallel research programs. One program is an experimental study of antiskid braking systems and the second program is the development of an aircraft ground handling simulator.

Two antiskid systems have been investigated to date: the first was an older velocity-rate-controlled system and the second was a more recent system designed to operate at a constant slip ratio. Initial results indicate that for both systems there was a rapid deterioration in tire cornering capability with increased braking effort, and the braking performance was degraded on wet runway surfaces. As expected, however, the braking performance of the newer antiskid system was shown to be somewhat better than that of the older system on both dry and wet surfaces.

The adequacy of a simulator hardware/software program to represent aircraft ground handling characteristics has been evaluated for a wide variety of operational conditions during demonstration flights made by several experienced test pilots. Based on their recommendations, some changes are currently being made to improve the simulation capability before it is implemented at Langley Research Center.

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INTRODUCTION

Operating statistics of modern aircraft indicate that the antiskid braking and steering systems used on these airplanes are both effective and dependable. The several million landings that are made each year in routine fashion with no serious operating problems attest to this fact. As aircraft avionics improve, however, the number of adverse weather landings also increases and thereby imposes greater demands on aircraft braking and steering systems. If compromises in the safety of aircraft ground operations are to be avoided, the performance of these braking and steering systems under slippery runway conditions must continue to improve.

In an effort to meet this need, NASA is currently conducting two parallel research programs. One program is an experimental study of the performance of several different aircraft antiskid braking systems under the controlled conditions afforded by the Langley aircraft landing loads and traction facility. The second is the development of a motion base aircraft landing and take-off simulator program which, when completed, will be implemented at Langley for use, among other applications, as a research tool to study aircraft braking and steering operations under adverse weather conditions without risk to aircraft and flight crew.

The purpose of this paper is to present findings to date on the antiskid research program and to describe briefly the ongoing development and status of the aircraft landing and take-off simulator program.

ANTISKID BRAKING RESEARCH PROGRAM

Objectives

The objective of the antiskid braking research is to find the sources of degraded performance which sometimes occur under adverse runway conditions and to obtain data necessary to the development of more advanced systems in an effort to insure safe ground handling operations under all-weather conditions. Secondary objectives are to acquire tire-to-ground friction characteristics under braking conditions which closely resemble those of airplanes under heavy braking and to relate braking data from single-wheel landing loads track tests with those available from full-scale flight tests.

Apparatus

Test facility.- The antiskid tests are being performed at the Langley aircraft landing loads and traction facility utilizing the test carriage shown in figure 1. Figure 2 is a photograph of the DC-9 tire wheel and brake assembly used in the test program mounted on the instrumented dynamometer which measures the various axle loadings. DC-9 equipment is being used because of the availability of flight test data from an earlier DC-9 program. The tire is a 40 × 14, type VII bias ply aircraft tire of 22 ply rating and both new and worn tread conditions are being investigated. The 365-m runway has a smooth flat concrete surface and tests are being conducted with the surface under dry, damp, and flooded conditions. With the exception of transient runway friction tests, the entire runway is maintained at one uniform surface wetness condition and antiskid cycling generally occurs for approximately 300 m.

Skid control systems.- To date, a velocity-rate-controlled, pressure-bias-modulated, skid control system, hereafter referred to as system A, and a slip command system, hereafter referred to as system B, have been investigated. System A is of interest in that it is a relatively early skid control technique (about 10 to 15 years old) but one that is still in widespread use on many commercial and military aircraft. System B is a more recent design based on maintaining the braked wheel at a constant slip ratio while using the nose wheel speed for a reference speed input to compute that ratio. Both antiskid control systems used the same hydraulic components and line lengths for a single wheel of the dual-strut four main-wheel, McDonnell-Douglas DC-9 series 10 airplane. Schematic diagrams of both systems are shown in figure 3. Pressure from a fully open pilot metering valve (to exert maximum braking) is regulated by the antiskid control valve and is fed to the brake. For system A (fig. 3(a)), braked wheel speed is fed to the antiskid electronic control box which senses the change in angular velocity (acceleration) of the braked wheel and generates a voltage to the control valve that is a function of the number and depth of previous skids. The antiskid control box of system B (fig. 3(b)), on the other hand, compares the speed of the braked wheel with that of the unbraked nose wheel and generates a current to the control valve to maintain pressure sufficient to control the braked wheel at 15 percent slip with respect to the unbraked nose wheel.

Test Results

Antiskid response.- Typical time histories of parameters which illustrate the nature of the response characteristics of the two antiskid systems are presented in figure 4. These parameters include the wheel speed, skid signal, brake pressure, and drag-force friction coefficient, and serve to show the adaptive characteristics of the antiskid systems as they experience an abrupt change in runway friction. At the start of the test, for system A (fig. 4(a)), the tire is operating on a dry runway and when a pressure of 20 MPa is applied to the brake, the drag friction coefficient developed between the tire and the runway increases to approximately 0.65. Approximately 3.5 seconds into the test, the runway condition changes abruptly from dry to flooded and the wheel, still under heavy braking, immediately enters into a deep skid which produces a full skid signal to the antiskid control valve. The valve, in turn, reduces the brake pressure to allow spinup of the braked wheel. When the wheel spins up to free rolling speed, the skid signal drops but not completely and allows brake pressure to be reapplied at a reduced rate which is a result of the pressure bias modulation circuit of system A. Five subsequent cycles ensue on the flooded surface as the system allows the pressure to build up to produce a skid and then decrease to permit wheel spinup. The inability of system A to prevent these deep skids on a flooded runway is attributed, at least in part, to the fact that the brake torque capacity greatly exceeds the resisting drag force, to the low spinup torque available on wet surfaces, and to the 40 ms response time required for the antiskid system to react to abrupt changes in wheel speed. The response time delay appears to be the result of electronic lags in the antiskid control box which occur when the wheel speed ac signal is converted to a dc voltage that is supplied to the antiskid control valve.

The test with system B, presented in figure 4(b), also shows a buildup in friction coefficient on the dry surface with brake application. In this test the dry surface was sufficiently long for antiskid cycling to occur. Note that the high-frequency oscillations in wheel speed correspond to skid signals and brake pressure releases and result in a fairly uniform drag-force friction coefficient. At approximately 6.2 seconds, the runway condition changes abruptly from dry to flooded and, as a result, the wheel enters a deep skid. This deep skid produces a full skid signal which reduces the brake pressure to near zero. After the initial transition, system B controls the brake pressure very well, prevents further deep skids, and, most importantly, maintains a fairly constant drag coefficient.

Typical tire frictional response to antiskid braking on dry and flooded runway surfaces is presented in figure 5 where the drag- and side-force friction coefficients for the tire yawed to 6° and operating at a nominal speed of 75 knots are plotted as a function of wheel slip ratio. A slip ratio of 0 corresponds to a freely rolling wheel and a slip ratio of 1 corresponds to a locked wheel skid. The data presented in the figure were generated by system A and illustrate the cyclic nature of the friction developed during antiskid braking control. The classical μ slip curve (ref. 1) is a smooth curve that reaches a peak somewhere between 10 percent and 20 percent slip (μ denotes friction coefficient). These data show that under realistic conditions, however, the curve is not smooth because of runway roughness, flexibility in the wheel support which would be reflected in the measured drag and side forces, variations in the runway friction characteristics, and the spring coupling between the wheel and the pavement provided by the tire. The data in the figure illustrate the traction losses associated with flooded runway operations. For example, on the dry surface the maximum drag-force friction coefficient reaches approximately 0.6 but on the flooded surface it never exceeds 0.2. A similar loss is noted in the developed side-force friction coefficient when the surface is flooded. The figure also demonstrates the rapid deterioration in the tire cornering capability with increased braking effort. For example, at a slip ratio of only 0.3, the side-force friction coefficient had decreased approximately 60 percent on the dry runway and to negligible values on the flooded runway.

Antiskid performance.- A measure of the antiskid performance can be obtained from the ratio of the average drag-force friction coefficient developed by the system to the average maximum available drag-force friction coefficient developed at the tire/pavement interface. This ratio, called the braking performance ratio for the purposes of this paper, is presented in bar graph form for systems A and B in figures 6(a) and 6(b), respectively.

The values in this figure are the numerical averages of all the data for a given test condition; for example, the 3° bar graph for the dry surface in figure 6(a) is the average of all dry runs at 3°, regardless of speed, vertical force, tire configuration or system pressure. For system A, the average performance ratio on a dry surface is shown to increase with increasing yaw angle and tire vertical force and to decrease when a new tire was replaced by one with essentially no tread. On the wet runway surfaces, the average performance ratio also decreases with a worn tire and increases with tire vertical force. There was no conclusive trend in braking performance at yaw angles of 3° and 6° but, in general, braking performance was not appreciably degraded by yaw angle; thus, the braking characteristics can be expected to be good during crosswind operations. For system A the best braking performance was obtained with a new heavily loaded tire running on a dry surface. In general, similar trends were noted with system B (fig. 6(b)). As expected, this newer system exhibits higher performance ratios for every test condition, but both systems consistently have reduced performance ratios on slippery surfaces. Thus, the stopping capability potential of an airplane on a wet runway surface is hampered not only by the reduced friction level but also by the inability of the antiskid system to effectively take advantage of the friction available.

AIRCRAFT LANDING AND TAKE-OFF SIMULATOR DEVELOPMENT

One of the applications of the data from the antiskid braking research program is to provide inputs necessary to the development of landing and take-off simulation technology. The following paragraphs discuss the background, current status, as well as the plans for and applications of this development.

Background

It is common knowledge that the ground operation safety margins of aircraft are reduced by combinations of such factors as slippery runways, the presence of crosswinds, poor pilot visibility, excessive touchdown velocity, and equipment malfunction, among others. Full-scale tests can be used to explore the braking capability of an airplane by simply noting the distance required to bring the vehicle to rest from some preselected ground speed. The directional control capability cannot be evaluated through full-scale testing because such tests would compromise the safety of the airplane and crew and because of the unpredictability of the key ingredient, the surface winds. In an effort to acquire the capability to safely explore aircraft directional control and braking performance under any runway environment, a major research program was recently undertaken to explore the feasibility of expanding current flight simulation technology to include the complex interactions between the runway and the landing-gear system. Such an expansion would require a definition of the runway environment (including surface crown and roughness), the magnitude and direction of crosswinds, tire/surface friction levels (including the relationship between braking and cornering), airplane characteristics (landing-gear dynamics, brake system behavior, and the contributions from reverse thrust and auxiliary braking devices), and a good runway visual scene.

Current Status

The initial simulation involved the F-4 airplane which was chosen because of the considerable amount of available tire traction data on the airplane from landing loads track tests and full-scale braking tests. A photograph of the motion base simulator used in the program development is given in figure 7. A typical time history of a simulated F-4 landing as performed by one of the test pilots on an icy runway is presented in figure 8. For this test run, the pilot touched down at approximately 125 knots in an 8 m/sec crosswind after negotiating a somewhat higher crosswind during approach. The figure shows the rollout behavior of the airplane which included some rather substantial lateral excursions.

The results of the feasibility study with the F-4 airplane were sufficiently encouraging that the development was extended to include the DC-9 jet transport. Table I is a summary of the pilot assessment of the F-4 and the DC-9 simulations during approach and touchdown, landing rollout, and aborted take-off demonstrations. Thus far, 348 simulator demonstration runs with six different pilots have been conducted with the F-4 and 186 runs with two pilots with the DC-9. Table I presents comments from two pilots in each airplane during the most recent demonstrations. These runs demonstrated the need for airplane deceleration cues (the current motion-based simulator has five degrees of freedom and fore-and-aft motion is not among them), a cockpit environment closely allied to the airplane being examined (both the F-4 and the DC-9 simulations were performed on an F-4 simulator), and good visual scene simulation (some difficulty was experienced in getting the terrain map translator to the proper simulated eye level for both airplanes).

Plans and Applications

Current plans in the aircraft landing and take-off simulation program include furthering, under contract, the development of the DC-9 transport simulation. This extension calls for the use of a transport cockpit on a motion base simulator with six degrees of freedom, and the incorporation of antiskid brake system simulation with hardware as needed. It is also planned to implement this simulator capability at Langley Research Center by starting with the DC-9, since the simulator technology for that airplane exists, and then expanding to a generalized model to accommodate the simulation of a variety of aircraft. Such a simulation would provide a research tool for evaluating, in perfect safety, factors which influence the ground handling performance of an aircraft up to and beyond its normal operating limits, or for making trade-off studies to evaluate aircraft design concepts (that is, landing gear, tire, brake, and antiskid modifications). In addition, an aircraft ground handling simulator could be used to establish safe operational limits for various airplane and runway combinations and to optimize piloting techniques under adverse runway conditions.

CONCLUDING REMARKS

This paper has presented the status of recent braking and cornering research at Langley Research Center. Two antiskid systems have been tested to date and the degraded performance noted on slippery runways was attributed to electronic lags, low wheel spinup forces, and to high brake torque capacity relative to the resisting drag force. Antiskid performance was highest under a heavy loading condition with a new tire on a dry runway. An aircraft landing and take-off simulator program has been written to safely study aircraft directional control problems on slippery runways in the presence of crosswinds. Initial runs in an aircraft landing and take-off simulation program appeared to be quite promising and the development is being expanded to include a transport cockpit utilizing a six degrees of freedom motion base simulator with the addition of antiskid brake action and an improved visual scene. A simulator, generalized to accommodate a variety of aircraft, is scheduled to be installed at Langley Research Center.

REFERENCE

1. Dreher, Robert C.; and Yager, Thomas J.: Friction Characteristics of 20 × 4.4, Type VII, Aircraft Tires Constructed With Different Tread Rubber Compounds. NASA TN D-8252, 1976.

TABLE I

PILOT EVALUATION OF SIMULATOR DEMONSTRATION RUNS				
SIMULATION	F-4 AIRPLANE		DC-9 AIRPLANE	
	PILOT A	PILOT B	PILOT C	PILOT D
APPROACH AND TOUCHDOWN	GOOD	GOOD	GOOD	FAIR
LANDING ROLL-OUT				
DIRECTIONAL CONTROL	GOOD	GOOD	FAIR	GOOD
BRAKING RESPONSE	FAIR	FAIR	POOR	GOOD
ABORTED TAKE-OFF				
DIRECTIONAL CONTROL	GOOD	GOOD	FAIR	FAIR
BRAKING RESPONSE	FAIR	FAIR	POOR	FAIR

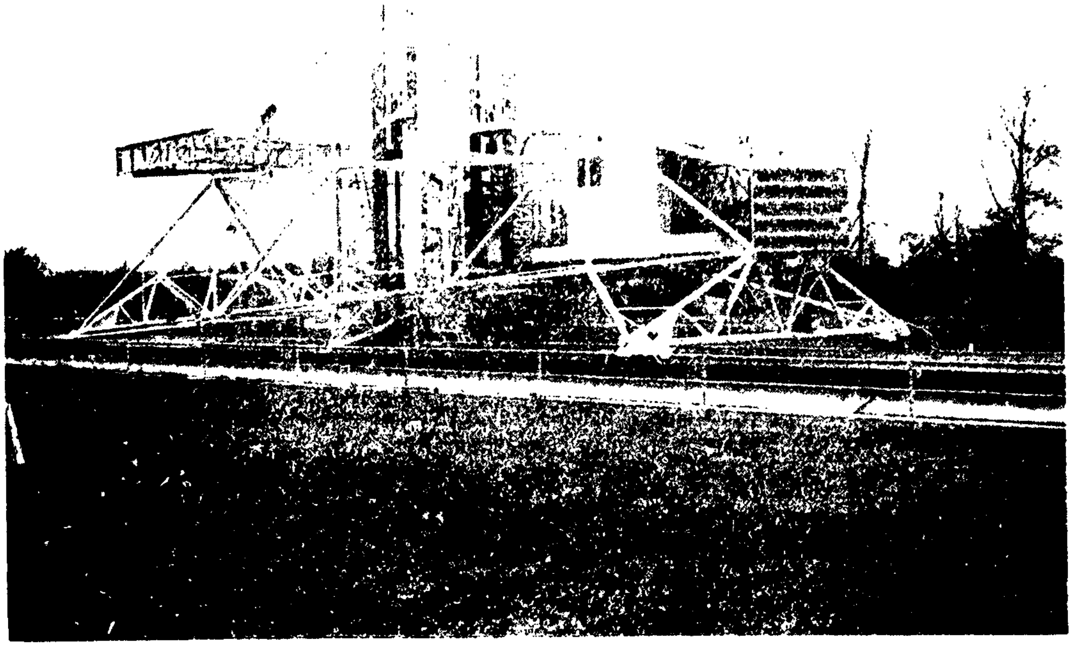


Figure 1.- Test carriage.

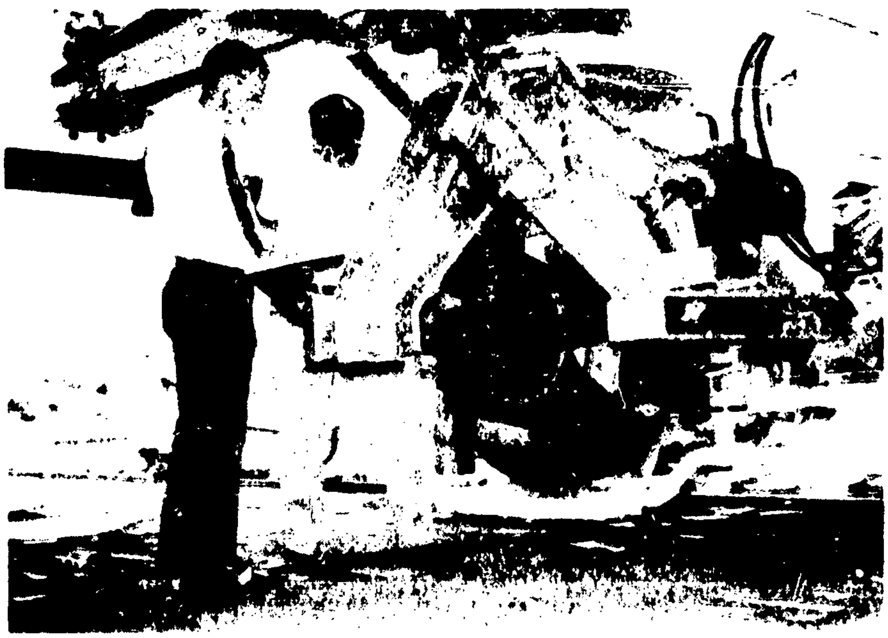
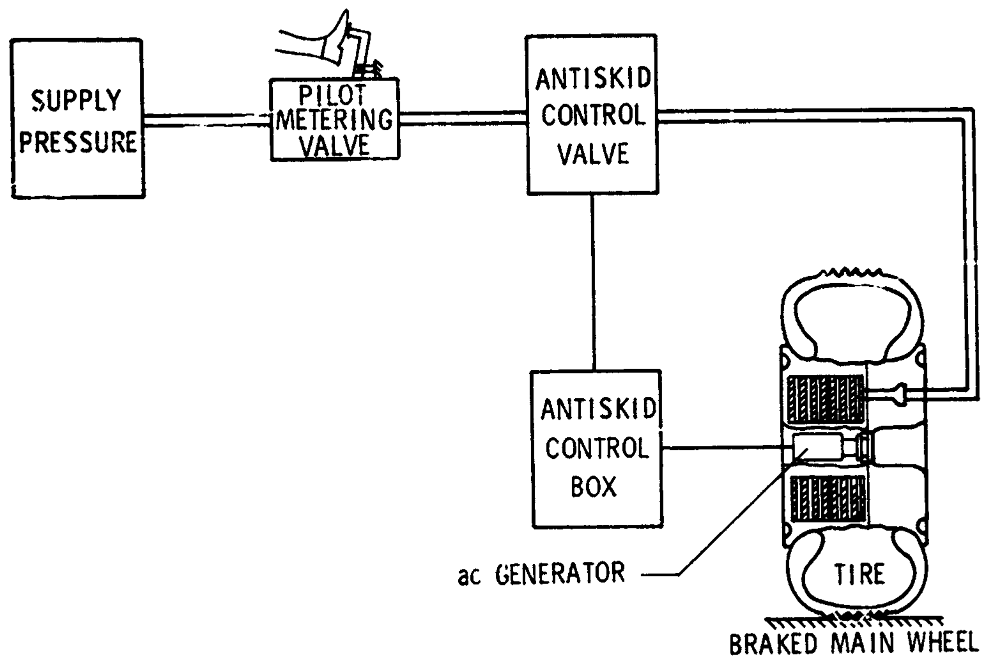
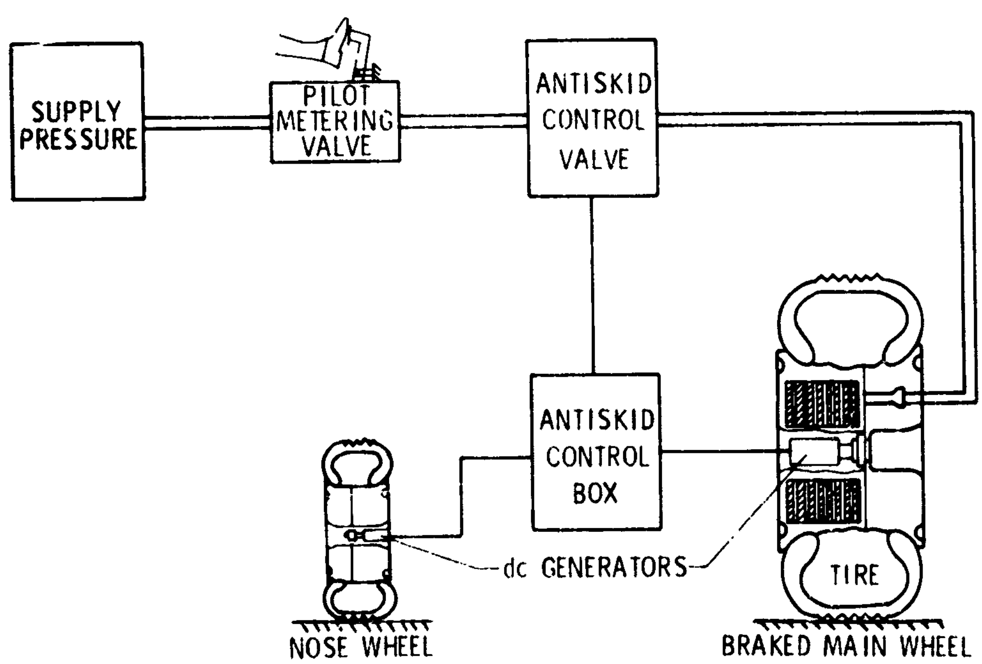


Figure 2.- Test tire and instrumented dynamometer.

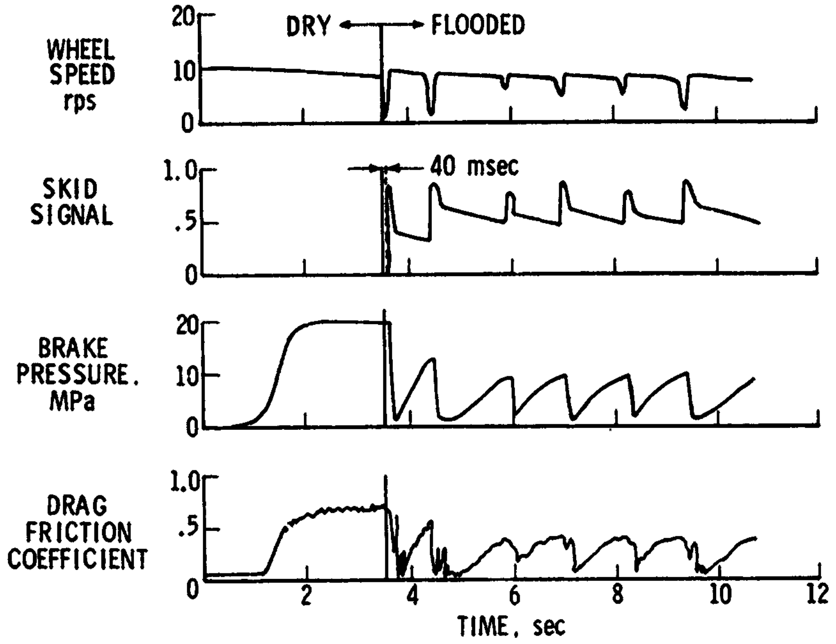


(a) System A.

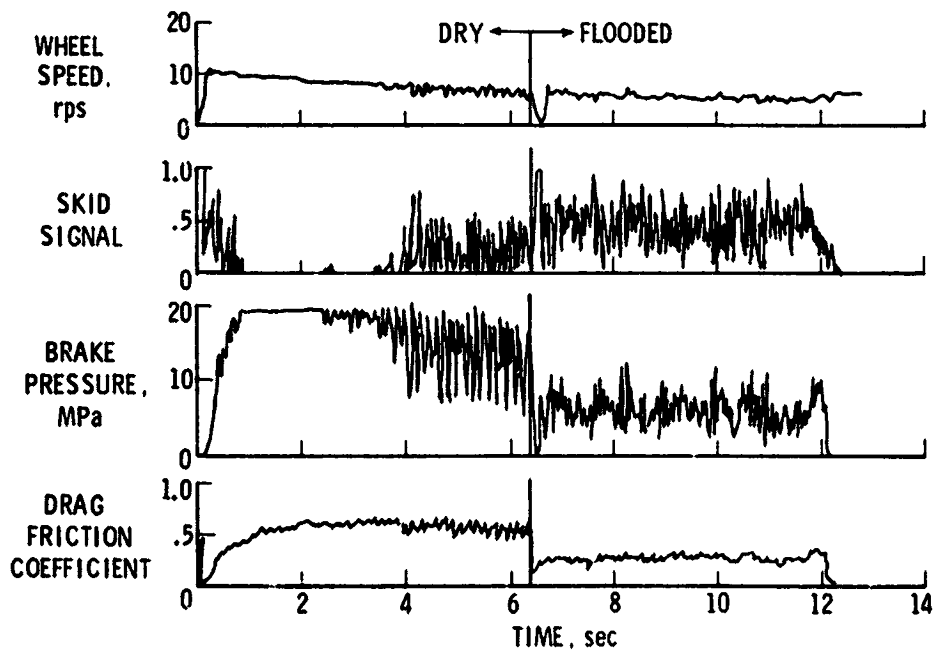


(b) System B.

Figure 3.- Skid control system.



(a) Brake system A; 0° yaw; 79.2 kN vertical load; 20.7 MPa brake supply pressure; new tread; 49 knots nominal carriage speed.



(b) Brake system B; 0° yaw; 83.2 kN vertical load; 19.0 MPa brake supply pressure; new tread; 41 knots nominal carriage speed.

Figure 4.- Typical antiskid system responses to transient runway conditions.

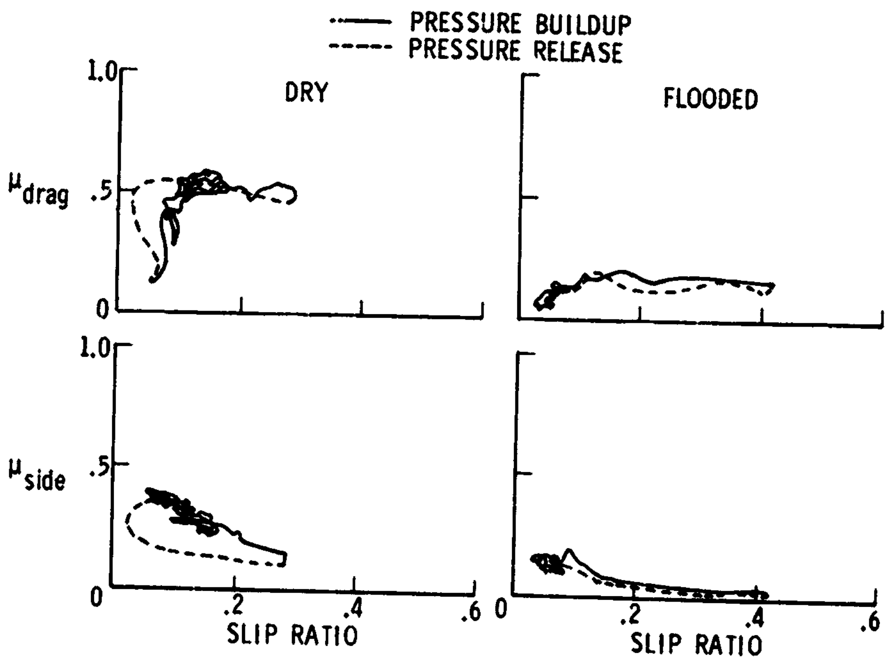
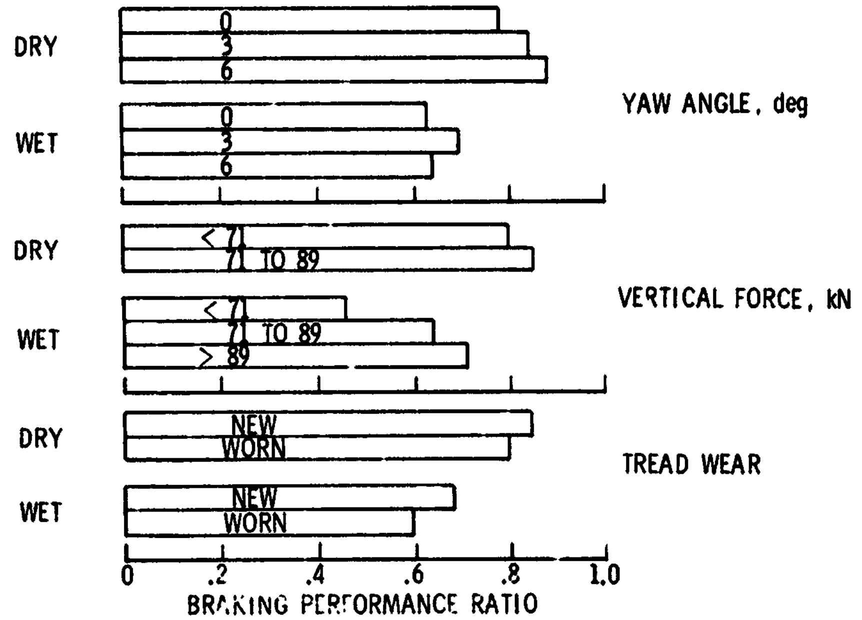
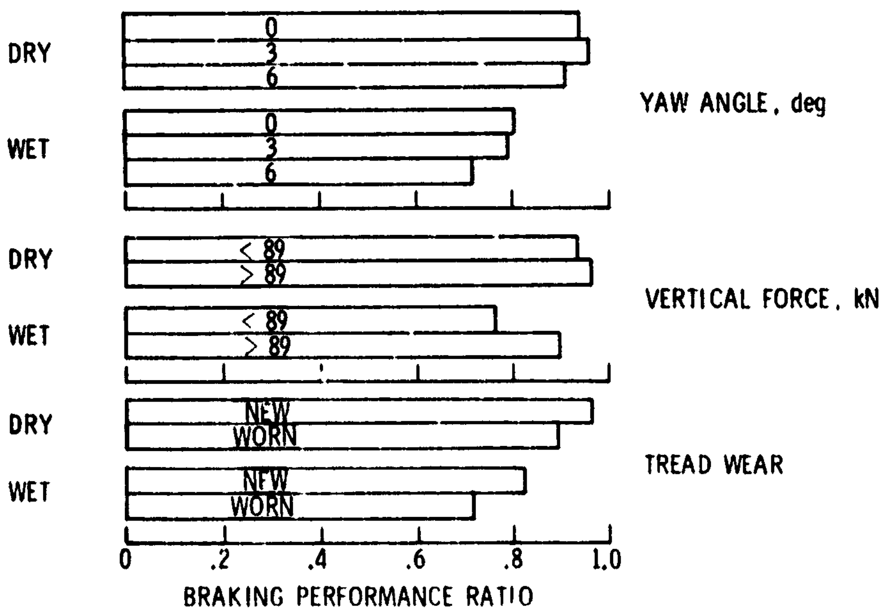


Figure 5.- Brake system A friction coefficients during cyclic braking. 6° yaw; 78.3 kN nominal vertical load; 20.7 MPa brake supply pressure; new tread; 75 knots nominal carriage speed.



(a) Brake system A.



(b) Brake system B.

Figure 6.- Effect of test parameters on braking performance ratio.

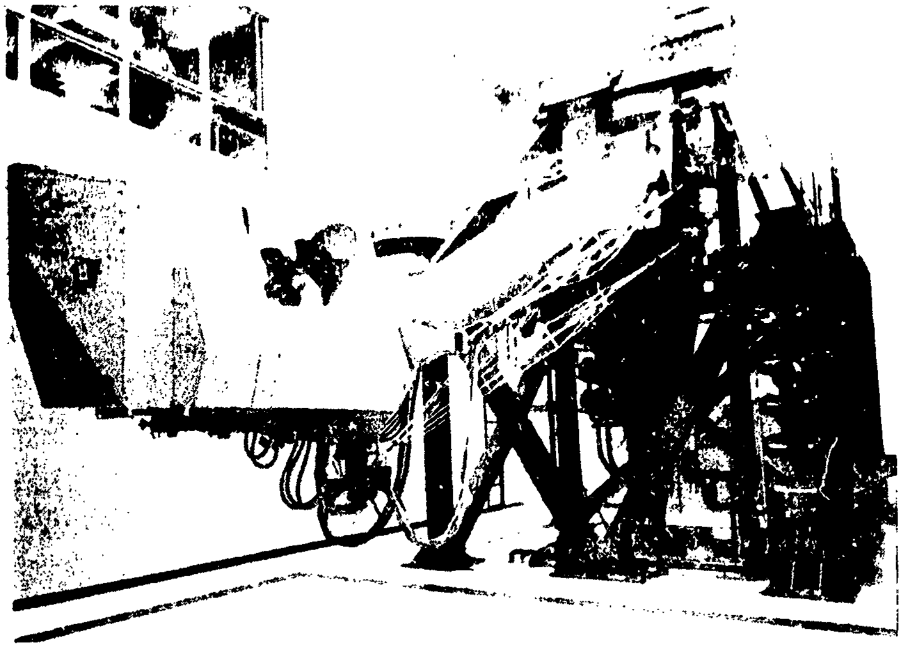


Figure 7.- Motion base simulator.

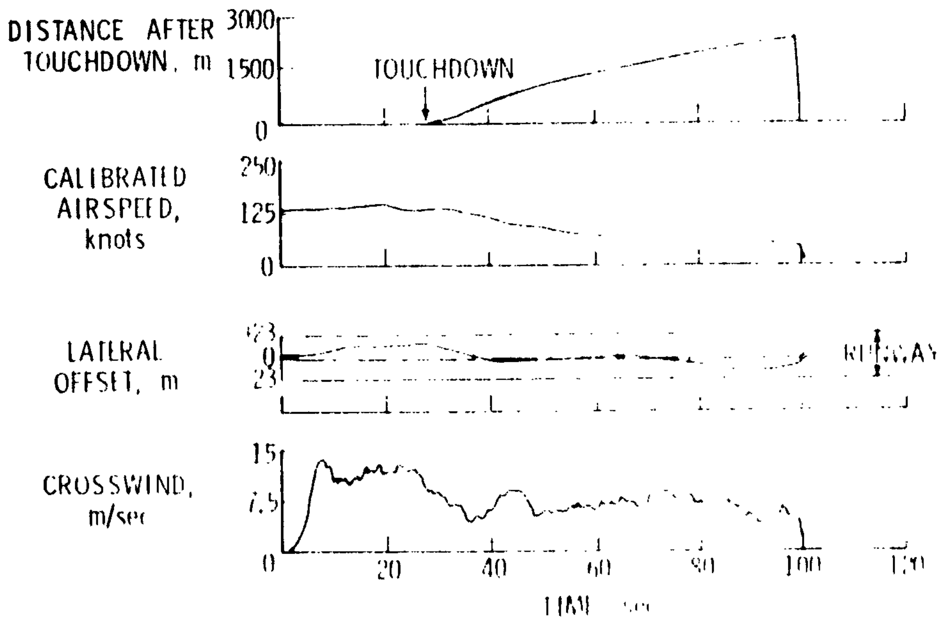


Figure 8.- F-4 airplane landing on ice runway.