Effects of Tread Wear on the Wet Runway Braking Effectiveness of Aircraft Tires

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The importance of a good tread design in improving the braking effectiveness of an aircraft tire on a wet runway has been well established. It is of equal importance, however, that the tread be maintained in good condition and replaced when tread wear becomes excessive. To explore in detail the effects of tire tread wear on braking effectiveness, a series of wet runway braking tests was run at the Langley landing-loads track in which smooth and dimple tires were used to represent completely worn tires. Five evenly spaced circumferential grooves were then cut into the tires to depths representing varying degrees of tread wear. Two types of tire wear were simulated: uniform wear with all grooves cut to the same depth, and nonuniform wear with the center groove wearing completely smooth while significant depths remain in the outer grooves. A gradual degradation in braking effectiveness was experienced up to about the 80% worn tire condition, at which point the wet runway friction coefficients dropped markedly. The completely worn tire was observed to develop, at the higher speeds, only about one-half the braking effectiveness of a new tire.

Introduction

PREVIOUS tire research as exemplified by Refs. 1 and 2 has indicated that the wet runway braking effectiveness of an aircraft tire is highly dependent on the original tire tread design. An important corollary to this fact is that even a good tread design may lose effectiveness as the tire becomes worn through normal usage. It was the purpose of this investigation to determine at what degree of wear a tire tread begins to lose effectiveness, and when the tire should be removed most economically from service without compromising safety requirements. Two forms of tire tread wear were simulated to represent uniform and nonuniform wear of grooves.

Test Apparatus and Procedure

Test Facility

The investigation was conducted at the Langley landing-loads track, which has for a number of years been used to investigate many different facets of the landing and ground-handling problems of aircraft. For the benefit of those who may not be familiar with this facility, the landing-loads track, as shown schematically in Fig. 1, consists of a large hydraulic water-jet catapult that accelerates the 60-ft-long test carriage to speeds up to 120 knots. The catapult expels a 7-in.-diam jet of water under the influence of air at pressures up to 3200 psi. This jet is received by a bucket on the back of the carriage which turns the water down and around through approximately 180° and discharges it toward the rear. The catapult system develops a thrust of as much as 350,000 lb, accelerating the 100,000-lb test carriage to top speed in about 3 sec, in a distance of 300–400 ft. After being catapulted to the desired speed, the carriage coasts freely for about 1200 ft, during which time the drop frame and the landing gear are released from some predetermined height and the test is accomplished. At the end of a test run, the carriage engages 5 arresting cables, which are connected to a system of 20 hydraulic arresting engines that bring the carriage to a stop in the 600 ft of track between the cable engagement point and the storage shed at the end of the track. Close control of such test conditions as forward speed, sinking speed, vertical load, and runway surface condition, coupled with versatile instrumentation capabilities, permits a detailed independent investigation of each of the many parameters affecting landing gear and tire performance. Excellent repeatability of test conditions can also be achieved for purposes of comparison and control. Figure 2 shows a photograph of the main test carriage.

Tires Used in Test

Tire tread wear was simulated by starting with a smooth tire and cutting progressively deeper grooves to simulate various uniform and nonuniform wear points. The tires used in the test were 32 × 8.8, type VII, 22 ply-rating aircraft tires. Also available and tested was a standard tire with a dimple tread which could be used in place of a smooth tire, since previous experience[1] had suggested little difference in wet-runway braking effectiveness between this tire and a smooth tire, and check points made during the present investigation also supported this conclusion. The dimple tire was grooved according to suggested airline standards of tire wear to represent nonuniform groove wear, with the center groove wearing at a faster rate than the outer grooves. The smooth tire was specially molded, having a casing skid depth as thick as a standard tire but with no tread pattern, and was used to simulate uniform tread wear, with grooves wearing

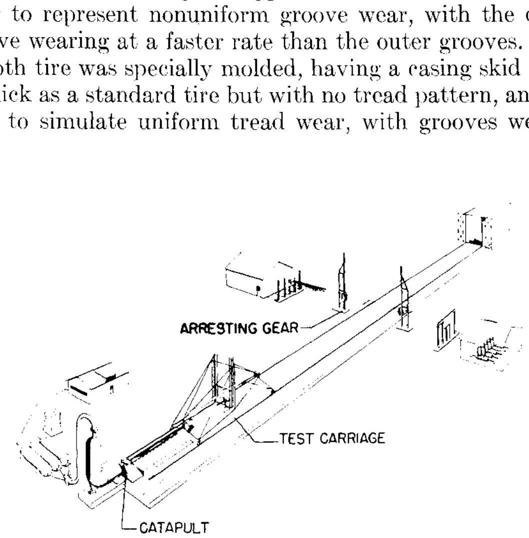

Fig. 1 Schematic of test facility (Langley landing-loads track).

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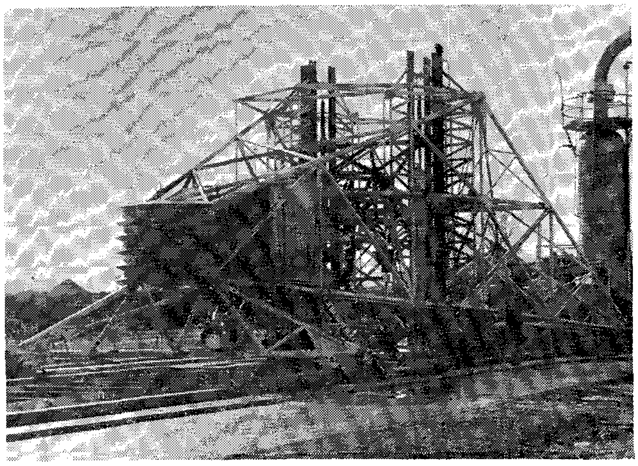
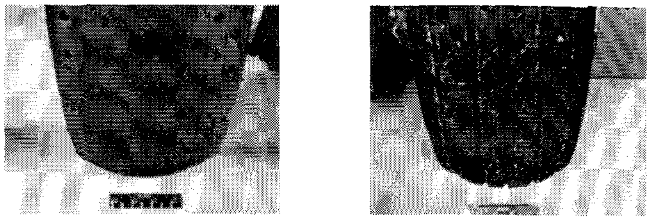


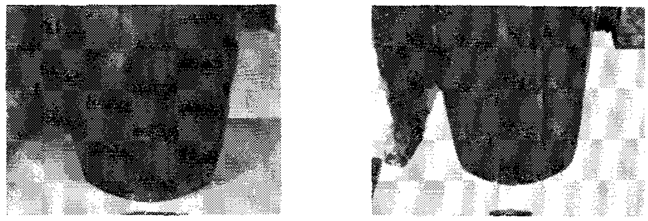
Fig. 2 Main test carriage at Langley landing-loads track, with catapult in background.

evenly. At the conclusion of the 20% uniform-wear condition, it was judged unsafe to cut the grooves as deeply as necessary to represent a new tire, so a standard, 3-groove fighter tire was obtained and modified by cutting in two additional grooves to represent a new 5-groove tire.

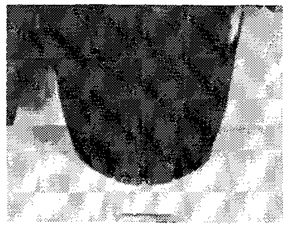
Five evenly spaced circumferential grooves were cut into the tires with the saw arrangement shown in Fig. 3. A special plate on the saw permitted close control of groove depth, while a mounting jig assured a constant groove width. Because of the necessity for making very shallow cuts in the smooth tire, groove widths for this tire were narrower than those for the dimple tire, as shown in Table 1. Photographs of the smooth and dimple tires, both grooved and ungrooved, as well as the modified new tire, are shown in Fig. 4. Groove depths were measured and recorded before and after each test run, both with a micrometer depth gage and a dial indicator, as shown in Fig. 5. Each groove was measured in six places around the circumference of the tire in approximately the same location. Groove depths recorded and tolerances maintained are shown in Table 1. Tire footprints were also taken at each wear point.



a) Dimple tire before and after grooving



b) Smooth tire before and after grooving



c) New tire

Fig. 4 Photographs of tires tested.

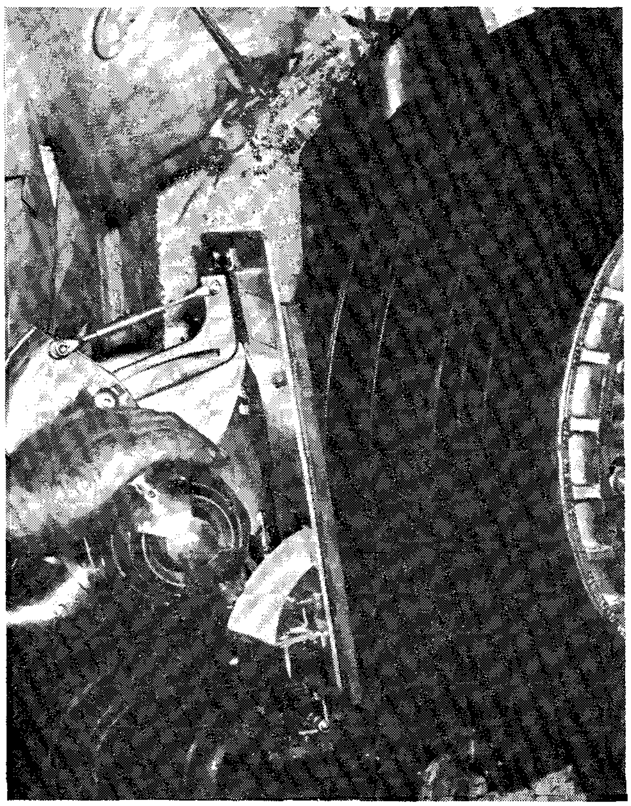


Fig. 3 Saw and jig arrangement used for grooving all test tires.

Test Conditions

The majority of testing was done on a wet runway for a tire pressure of 150 psi. The test section was provided with a sprinkler system to achieve essentially constant wetness con-

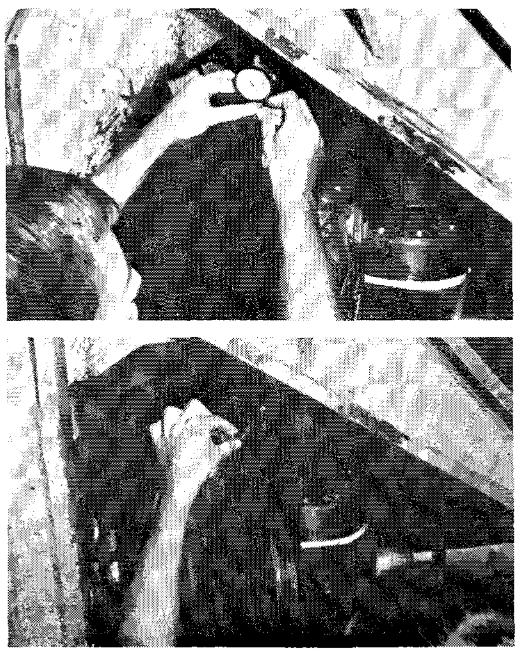


Fig. 5 Measuring groove depths with dial indicator and micrometer depth gage.

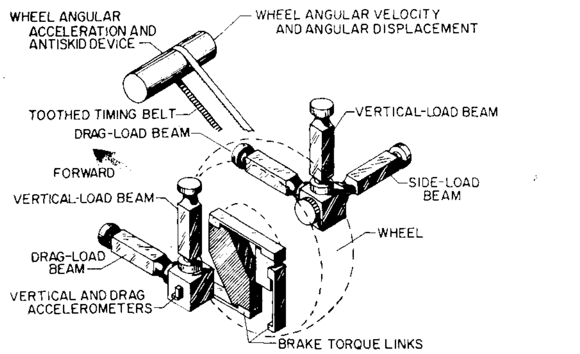


Fig. 6 Schematic of test fixture used for all tires tested.

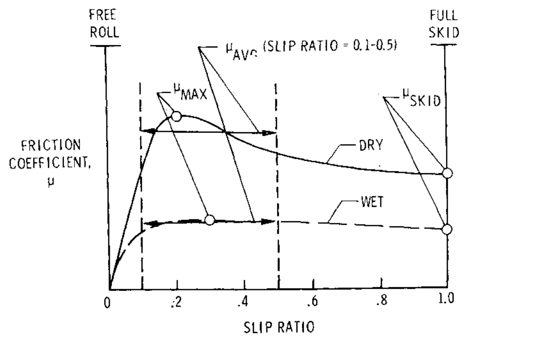


Fig. 7 Schematic comparison of various friction coefficients, showing how μ_{avg} was derived.

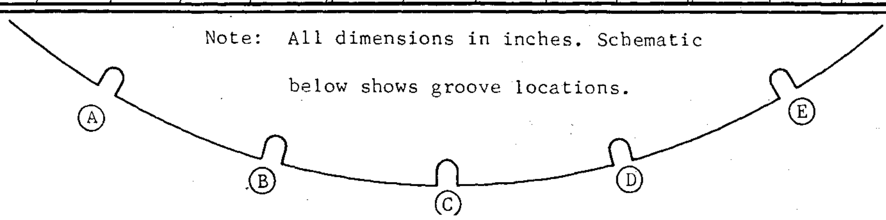
ditions, which, because of runway unevenness, varied in the test section from 0.1 to 0.3 in. of water. Test runs were also made for a tire pressure of 90 psi, both on the wet runway and on a runway surface covered with 1 in. of water. The static vertical load on the tire for all runs was 10,500 lb. Braking cycles were initiated by magnetic pickups placed at intervals along the track, giving control of number and location of braking cycles for each run. Pressure was metered to the brake through a micrometer needle valve, which acted as a controllable orifice. This was done so that brake-pressure rise time could be varied with the forward speed and anticipated friction conditions to give approximately the same braking distance per run. At the conclusion of the test, several runs were made with the new 5-groove tire on a damp surface, in which the surface was discolored but there were no puddles or standing water. This damp surface closely resembled a runway as it might be in the early morning following a heavy dew. A short series of runs were made on dry concrete to provide comparative data for the other braking conditions.

The test fixture was the same as used in previous investigations (Refs. 1–3) and is shown schematically in Fig. 6. Vertical and drag loads were measured and corrected by the accelerometers to compute instantaneous tire-ground friction

Table 1 Groove depths for tires investigated

Percent Wear	Desired Groove Depth					Groove Depth Before Series					Groove Depth After Series					Avg. Groove Width
	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	
a) Smooth tire - uniform wear																
0 (new)	.240	.240	.240	.240	.240	.242	.242	.238	.235	.241	.230	.230	.225	.223	.230	.375
20	.192	.192	.192	.192	.192	.188	.193	.192	.193	.187	.180	.186	.186	.186	.179	.220
60	.144	.144	.144	.144	.144	.142	.150	.145	.136	.135	.138	.147	.142	.130	.130	↓
75	.060	.060	.060	.060	.060	.064	.066	.064	.073	.061	.059	.060	.060	.068	.060	↓
80	.048	.048	.048	.048	.048	.049	.045	.049	.047	.046	.044	.040	.044	.040	.040	↓
85	.036	.036	.036	.036	.036	.036	.039	.039	.043	.036	.029	.035	.035	.038	.033	↓
90	.024	.024	.024	.024	.024	.024	.023	.024	.024	.023	.021	.018	.022	.020	.020	↓
95	.012	.012	.012	.012	.012	.015	.015	.016	.015	.016	.010	.010	.010	.010	.010	↓
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	- -
b) Dimple tire - non-uniform wear																
0	.250	.250	.250	.250	.250	.199	.227	.212	.202	.195	.189	.216	.198	.190	.184	.290
50	.216	.155	.125	.155	.216	.206	.150	.120	.137	.203	.195	.136	.104	.126	.192	↓
80	.194	.098	.050	.098	.194	.185	.098	.047	.103	.183	.177	.093	.037	.094	.172	↓
90	.175	.094	.037	.094	.175	.177	.093	.037	.094	.172	.170	.088	.032	.087	.168	↓
100	.073	.059	0	.059	.073	.071	.052	0	.051	.072	.058	.043	0	.041	.053	↓

Note: All dimensions in inches. Schematic below shows groove locations.



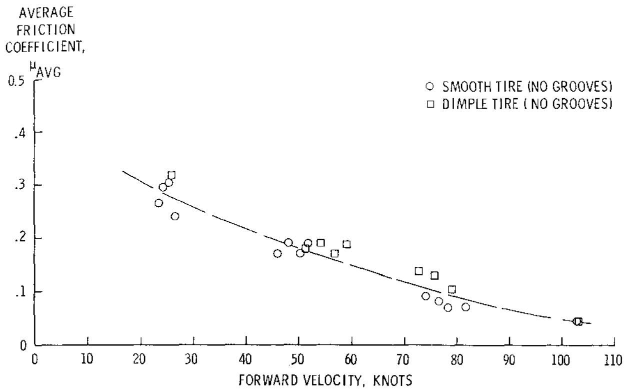


Fig. 8 Comparison of wet runway braking effectiveness of smooth and dimple tread tires. Tire pressure = 150 psi.

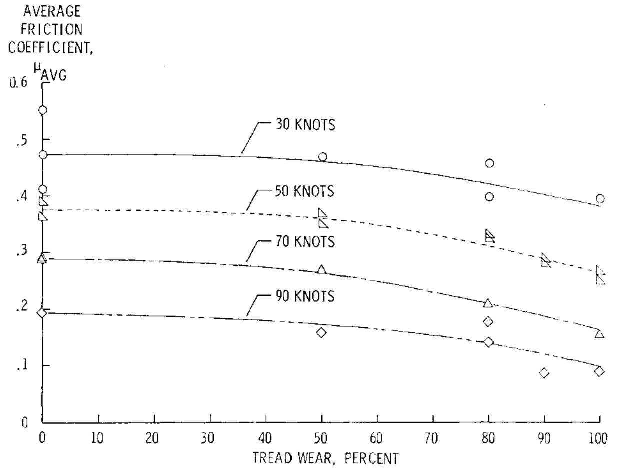


Fig. 10 Effects of nonuniform tread wear on wet runway braking effectiveness at selected velocities. Tire pressure = 150 psi.

coefficients throughout the entire brake cycle. Also recorded were angular displacement, velocity and acceleration, brake torque and brake pressure, wheel vertical displacement, and carriage forward velocity.

Presentation of Test Results

Instantaneous values of braking friction coefficient were computed for all braking cycles, from a free rolling wheel to a locked wheel. However, the test results discussed in this paper will express braking effectiveness in terms of μ_{avg}, the average friction coefficient developed between a slip ratio of 0.1 to 0.5, as shown schematically in Fig. 7. The presentation of data in this manner tends to smooth any uncharacteristic peaks or low points in individual brake cycles which may be caused by local slippery spots or runway contaminants. Also, as will be seen from Fig. 7, when discussing wet runways or other low-friction conditions, the friction-coefficient/slip-ratio curve flattens out, so that the average friction coefficient μ_{avg}, the maximum friction coefficient μ_{max}, and the skidding friction coefficient μ_{skid} all tend toward a common value. The average friction coefficient is also more likely to be the over-all friction coefficient obtained with modern antiskid systems.

Tire-Wear Effects

Nonuniform wear

Figure 8 shows the comparison of wet runway braking effectiveness of the smooth and dimple tread tires before cutting any grooves. Very little difference can be noted in the results for the two treads. Figure 9 summarizes the results of the nonuniform-wear investigation in which the dimple tire was used. As would be expected, friction coefficients for all wear points drop rapidly with increasing forward speed, with the worn tire developing only about one-half the friction of the new tire at the higher speeds. It should be recalled that when the nonuniformly worn tire is 100% worn, only the center groove is worn smooth while significant groove depths remain in the outer grooves, as shown in Table 1. This fact accounts for the relatively high friction levels at this wear condition as compared with the results obtained for the ungrooved dimple tire. The effects of tread wear are perhaps illustrated more clearly in Fig. 10, where a gradual degradation in braking effectiveness can be noted as wear progresses from a new tire to about the 80% worn condition, with further tread wear noticeably reducing the braking friction levels at all velocities.

Uniform wear

The same trends were noted in the uniform-wear investigation (Fig. 11) as for the nonuniform-wear investigation, with a noticeable decline in braking effectiveness occurring near the 80% wear condition. As previously mentioned, total tire wear prevented regrooving the smooth tire beyond the 20% wear point, but apparently the results would follow the trend

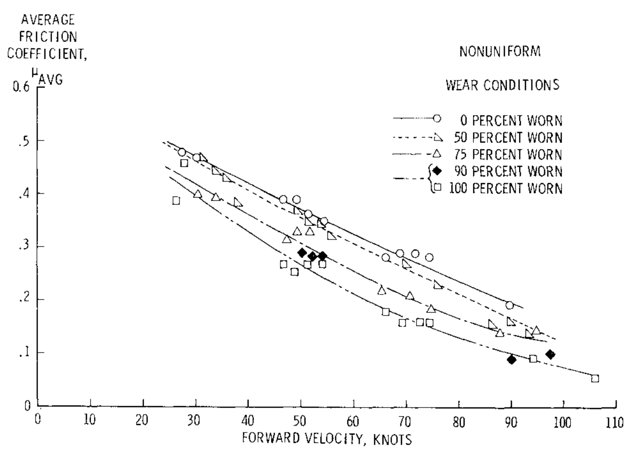


Fig. 9 Effects of nonuniform tread wear and forward velocity on wet runway braking effectiveness. Tire pressure = 150 psi.

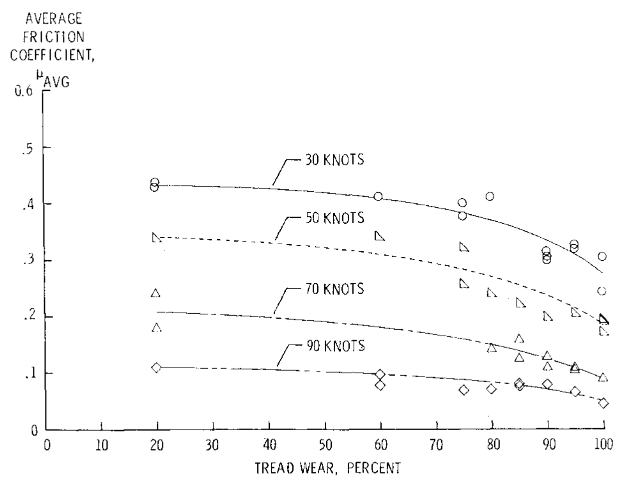


Fig. 11 Effects of uniform tread wear on wet runway braking effectiveness at selected velocities. Tire pressure = 150 psi.

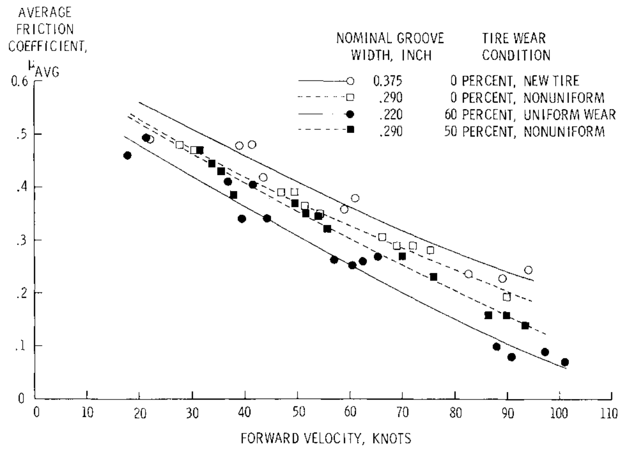


Fig. 12 Effects of tire groove width on wet runway braking effectiveness. Tire pressure = 150 psi.

in Fig. 10, with very little change in braking effectiveness occurring between the 0% and 20% wear conditions.

Other Effects

Groove-width effects

As stated previously, the groove width differed for the various tires tested. The importance of this difference is shown in Fig. 12. The new tire, having a nominal groove width of 0.375 in., is shown to develop notably better friction coefficients at all speeds than the 0% nonuniformly worn tire that had a nominal groove width of 0.290 in. Although the new tire had somewhat deeper grooves than the nonuniformly worn tire (see Table 1), it is felt that the groove width was the primary factor responsible for the increased braking friction, because of the relatively shallow water depths of 0.1 to 0.3 in. This conclusion is further supported in Fig. 12 by comparing the 50% nonuniformly worn tire (nominal groove width 0.290 in.) with the 60% uniformly worn tire (nominal groove width 0.220 in.), which had about the same groove depth in the three center grooves. The improved wet runway braking effectiveness of the wider groove is probably a result of better or more rapid escape of water from the footprint region and of higher local tire-ground bearing pressures. There is an obvious need for further investigation of the effects of tire groove width, spacing, and shape, in the hopes of optimizing tire tread design.

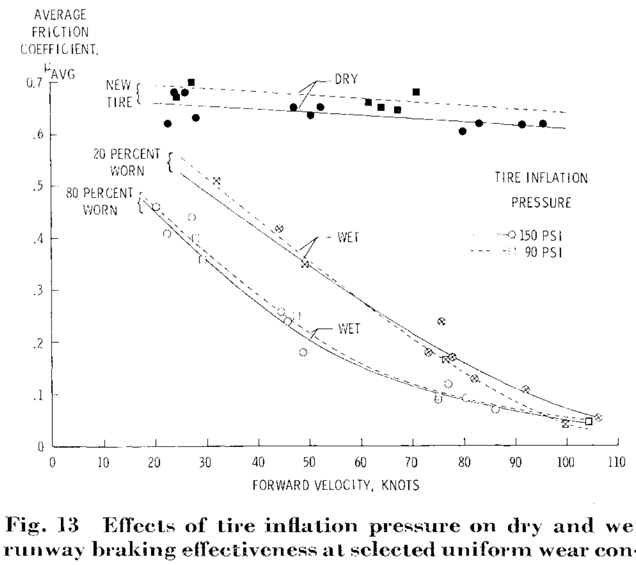


Fig. 13 Effects of tire inflation pressure on dry and wet runway braking effectiveness at selected uniform wear conditions.

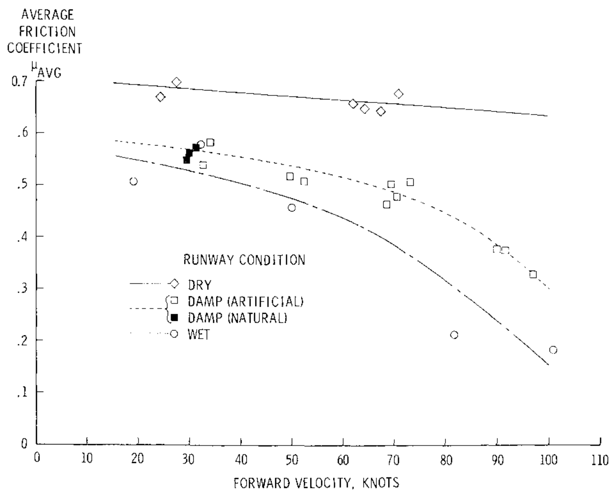


Fig. 14 Effects of runway surface condition on the braking effectiveness of a new tire. Tire pressure = 90 psi.

Tire-pressure effects

Figure 13 shows the effects of tire inflation pressure on braking effectiveness on dry and wet runways. The lower tire pressure resulted in somewhat higher friction coefficients on dry runway braking, an effect previously noted in Ref. 1. On wet runway braking, however, only slight differences were observed between the two tire pressures.

Shallow-water effects

It may be of interest to note the effect that even small amounts of water on the runway can have on braking effectiveness. Fig. 14 illustrates the loss in braking effectiveness for a tire pressure of 90 psi caused by a damp runway such as might be found early in the morning following a heavy dew. One run was actually made under these conditions, shown by the dark test points in the figure. Such conditions were simulated for the remainder of the test by wetting the runway and then brushing off all standing water. Also included for comparison in this figure are the results for this tire braking on a wet runway, with water depth ranging from 0.1 to 0.3 in. Fig. 15, which is for the higher tire inflation pressure of 150 psi, shows the same trends.

Deep-water effects

In order to explore the effects of tire tread wear on tire hydroplaning[4] and on braking in deep water, a series of runs

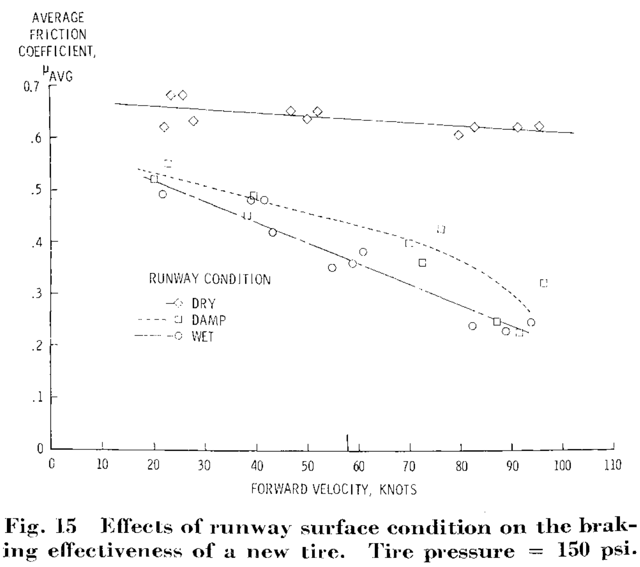


Fig. 15 Effects of runway surface condition on the braking effectiveness of a new tire. Tire pressure = 150 psi.

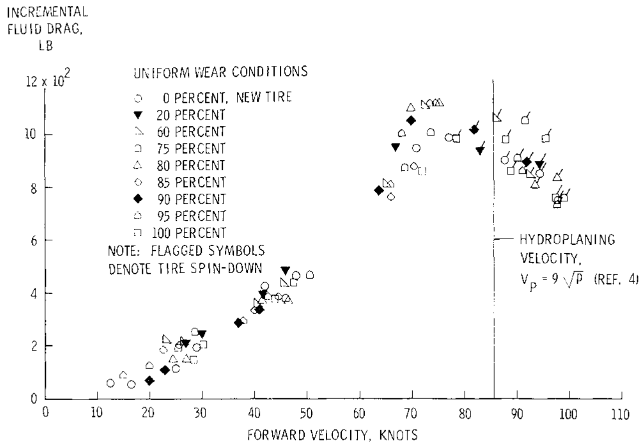


Fig. 16 Fluid displacement drag developed by a tire rolling unbraked through water 1 in. deep. Tire pressure, p = 90 psi.

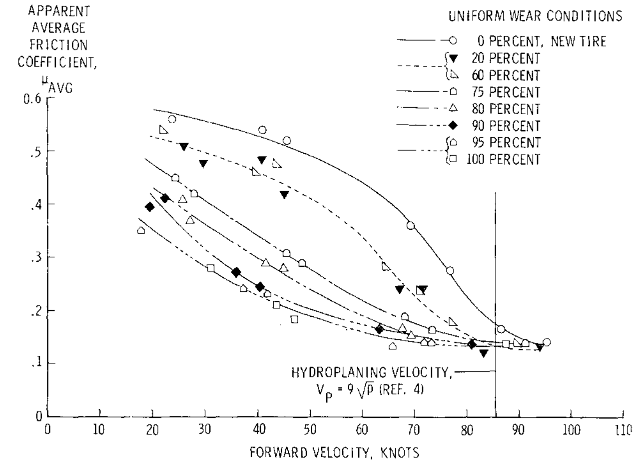


Fig. 18 Effect of uniform tread wear on the braking effectiveness of a tire in water 1 in. deep. Tire pressure, p = 90 psi.

was made concurrent with those just discussed, but with the tire inflation pressure at 90 psi. In this series of tests, all made in 1 in. of water, the tire was allowed to roll freely for a time before the brakes were applied to determine the magnitude of the fluid displacement drag created on the tire. The results of the free-rolling portion of the investigation are shown in Fig. 16, and indicate that tire tread depth has no discernible effect on fluid displacement drag. The tire hydroplaning velocity equation, as developed in Ref. 4, and shown in Fig. 16, is substantiated by these results as indicated by the peak in fluid drag and by tire spin-down. It should be noted that the fluid drag shown in Fig. 16 is incremental fluid drag—that is, the rolling resistance has been subtracted out to give only the added drag due to fluid displacement by the tire. The rolling resistance of the tire is shown in Fig. 17 for tire pressures of 90 and 150 psi. The higher tire pressure, as might be expected, results in lower rolling resistance.

The importance of tread wear when braking in deep water is shown in Fig. 18, where a very definite drop in braking effectiveness in 1 in. of water can be observed as tire wear progresses past the 60% worn condition. The much higher friction levels developed by the new tire are due, as previously explained, to the wider grooves in the tire. For all wear conditions, however, the friction coefficient reaches a minimum at or near the tire hydroplaning speed. The apparent friction coefficients of Fig. 18 include the effects of fluid displacement drag. In order to determine the contribution of the brake itself, the fluid displacement drag must be subtracted. This has been done for the new tire, as illustrated in Fig. 19. The net retarding effect of the brake at hydroplaning speeds is seen to be at a level comparable to the free rolling resistance of the tire (Fig. 17). This would indicate that while attempting to brake at speeds in excess of tire hydroplaning, the retardation developed on an aircraft must come from sources other than braking friction.

Concluding Remarks

This investigation has demonstrated the important effects of tire tread wear on the wet runway braking effectiveness of aircraft tires. A gradual degradation in braking effectiveness was experienced by two dissimilar tread designs as tread wear progressed from a new tire, or zero wear condition, to a 60–80% worn tire. As tread wear passed the 80% worn condition, however, braking effectiveness dropped markedly. These results indicate that aircraft tires should be replaced before the tread becomes wholly smooth if safety requirements are not to be compromised. There is a need for further investigation of the depth, width, spacing, and shape of tire grooves in order to optimize wet runway braking effectiveness.

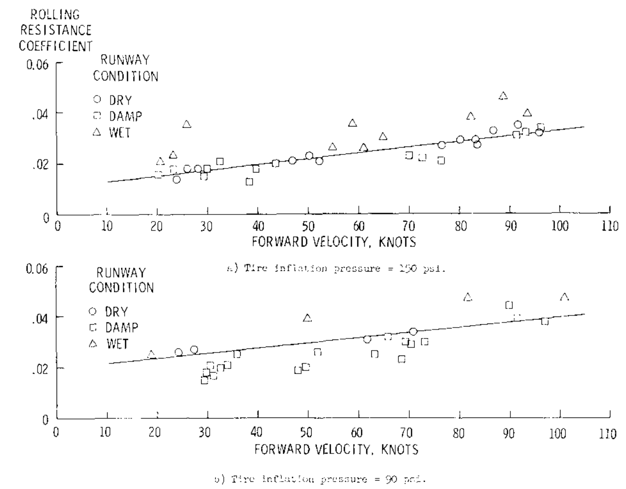


Fig. 17 Effect of tire inflation pressure on the rolling resistance of a new tire rolling unbraked on different runway surface conditions.

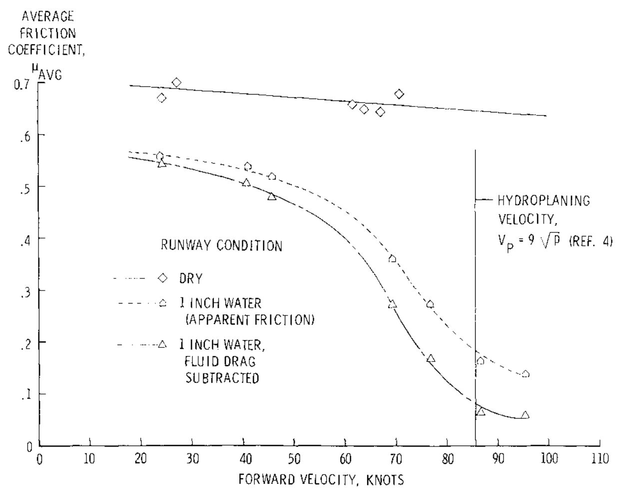


Fig. 19 Comparison of apparent and actual friction coefficients developed by a new tire braking in water 1 in. deep. Tire pressure, p = 90 psi.

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Some Aerodynamic and Operational Problems of STOL Aircraft with Boundary-Layer Control

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A summary is presented of problems encountered during flight tests of STOL aircraft using boundary-layer control for high lift. A number of vehicles using boundary-layer control by suction through distributed perforations have been flight tested in this country and abroad during the past ten years. Several aerodynamic characteristics peculiar to this method of increasing lift have become apparent. Specifically, the theoretical methods used for the determination of the distribution of the required perforations are described and the agreement between these theories and experimental measurements is discussed. The requirement for more fundamental information concerning the effects of suction on the characteristics of the turbulent boundary layer, such as surface shearing stress, is emphasized. The effects of weather and aging on the perforations is mentioned in this regard. Separation of the flow at the wing leading edge resulting from locally high adverse pressure gradients is discussed and several methods for delaying or preventing this separation are suggested. The effects of various intersections, protuberances, and propeller slipstream effects are analyzed. Various flap configurations are examined and their effects upon the flow over the wings and their influence upon the wake and over the tailplanes are discussed in detail. Finally, some operational limitations to the flight of such vehicles are mentioned.

Introduction

THE use of boundary-layer control (BLC) by suction through distributed perforations to delay or prevent the separation of the turbulent boundary layer has been under examination for several years. During this period, various conventional aircraft have been modified, both here and abroad, to employ this technique of BLC to attain STOL flight. From the flight tests conducted on these vehicles, several characteristic problems typical of this method of increasing life have become apparent.

The present report is intended to summarize some of these findings and to describe the methods or approaches used to alleviate or to avoid the particular problems. Flight test results from a number of aircraft using suction boundary-layer control for lift augmentation are examined and compared.

Description of Some Aircraft Using Suction Boundary-Layer Control

TG3-A Sailplane

Extensive experimental flight research has been conducted since 1952 at Mississippi State University using a TG3-A sailplane (Fig. 1). The primary objective of this research has been the study of the properties of the turbulent boundary layer and the influence upon these properties of suction through distributed rows of perforations in the wings of the aircraft. Though obviously not an STOL aircraft, the TG3-A has been flown at relatively high angles of attack with respect to conventional aircraft without such high-lift devices, and much of the information concerning the boundary layer under these conditions is pertinent to the general problem of STOL flight.[1]

A diagram of the boundary-layer control system used on this aircraft is shown in Fig. 2. The electrical energy required for the operation of the axial flow pumps was originally supplied by a 24-v, 35-amp-hr aircraft storage battery. Subsequently the energy was supplied by a small gasoline-driven motor-generator set in order that longer periods of flight test under continuous operation could be obtained.

Piper L-21

In order to study the effects of turbulent boundary-layer control on the STOL characteristics of a conventional liaison-type aircraft, an Army L-21 (Fig. 3) was modified in 1953 to accept a suction BLC system similar to that used in the research conducted on the TG3-A sailplane.[2] Modifications to this vehicle included the addition of a single axial-flow pump, which was belt-driven from the propeller shaft, installation of suitable ducting to conduct the air sucked from the wings to the pump, and, of course, the perforation of the upper surface of the fabric wing. A diagram of this aircraft, as modified, is shown in Fig. 4.

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