High-Speed Braking of an Aircraft Tire on Grooved Surfaces

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The Federal Aviation Administration is engaged in an experimental program to determine the effectiveness of grooves and other low-cost surface treatments that alleviate hydroplaning. A ground test facility provides speeds of up to 150 knots by the use of a jet-powered pusher car that also supports a tire-wheel assembly. The tires of a Boeing 727 aircraft are inflated to 140 psi and loaded vertically to 35,000 lb. The tire-runway braking is measured by the use of proper instrumentation. High-speed braking tests show that low-cost surface treatment can be provided in two ways: 1) by increasing the spacing of the square saw-cut grooves beyond 1¼ in., and 2) by installing V-shaped grooves using a reflex-percussive cutting process. In both cases, the braking effectiveness of an aircraft tire was found to be "acceptable" and hydroplaning was not experienced at speeds of up to 150 knots.

Introduction

An aircraft is brought to a complete stop on a runway by the combined forces of aerodynamic drag, reverse engine thrust, and wheel braking. The effectiveness of wheel braking deteriorates as the wetness on the runway surface increases. In an extreme case where a runway becomes flooded with water, an airplane can hydroplane during landing or takeoff and its braking and cornering capabilities are reduced significantly. Runway surface treatments, such as grooves, can minimize the danger of hydroplaning by reducing the water buildup on the runway and by facilitating forced water escape from the tire-runway interface.

The Federal Aviation Administration (FAA) is engaged in an experimental program to determine low-cost surface treatments that are effective at high landing speeds of jet aircraft. Surface treatments included in the program are: square grooves cut by rotary saws with diamond-tipped blades, V-shaped grooves installed by pneumatically driven hammer-type cutters, and a porous friction course characterized by its open-graded matrix. The effectiveness of these surface treatments was quantified in terms of maximum braking action available under a variety of test conditions. The basic parameter measuring the braking action is the coefficient of friction developed at the tire-runway interface.

Test Approach

Measurement of Incipient Hydroplaning

The coefficient of friction is computed by dividing the frictional forces developed at the tire-runway interface by the vertical load on the aircraft tire. During hydroplaning, the friction coefficient is theoretically zero; however, because of the presence of viscous and mechanical drags, the measured friction coefficient is not zero. Thus, for a direct measurement of the speed at which hydroplaning occurs, the viscous and mechanical drags must be subtracted from the measured friction coefficient. This is generally not practical, if only because of the necessity of a complex instrumentation system. Many indirect methods have been used in the past to identify the onset of hydroplaning.[1] In the present study, incipient hydroplaning is indicated when the measured friction coefficient is 0.05 or lower. In comparison, the average friction coefficient between the aircraft tire and the dry runway is approximately 0.7.

Measurement of Maximum Braking Action

Frictional forces at the tire-runway interface are developed as a result of relative motion between the tire surface and the runway. This relative motion is also known as circumferential tire slip; tire slip is an indication of the departure of the angular velocity of the braked tire from the free-rolling velocity. Frictional forces initially increase with slip, then reach a maximum value, and finally decrease as the tire slip increases beyond 20%. Tire slip is a complex function of speed, brake pressure, runway wetness, runway surface texture, and type of tire. For a given set of speed, wetness, tire, and runway type, the friction coefficient can be measured by varying the brake pressure in successive tests. By closely monitoring the magnitude of the friction coefficient and tire slip, the maximum available friction coefficient is obtained.

Experimental Program

Test Facility and System

The high-speed braking action of an aircraft was duplicated at the ground test facilities of the Naval Air Engineering Center, Lakehurst, NJ. Powered with four J48-P-8 aircraft engines, a vehicle (Fig. 1) pushes a carriage containing the aircraft tire-wheel assembly (Fig. 2) on steel guide rails; little over a mile of the track is available to achieve test speeds in excess of 150 knots. The jet vehicle is separated from the carriage after achieving the predetermined speed, and the carriage coasts into the test bed (Fig. 3) located at the end of the track.

The tire-wheel assembly is subjected to operational conditions representative of values used by the airlines and aircraft. The test system provides adequate control of the variables and good reproducibility of the measured data.

Surface Treatments

Grooves and porous friction overlay were installed in concrete sections (Fig. 4). Dimensions of the reflex-percussive grooves and square saw-cut grooves are shown in Fig. 5. Each test section was approximately 40 ft long; longer sections were not necessary because earlier research[2] has shown that the tire-pavement interface friction is fully developed in 1-6 ft, depending upon the speed of operation. Square grooves have

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been widely used for runways since they were first introduced by the British in 1956 on several airfields in England. The National Aeronautics and Space Administration (NASA) studied the saw-cut grooves in the mid-1960's[3] and early 1970's[4]. The FAA test program complements the NASA program by extending the speed range to 150 knots.

The V-shaped grooves are produced by a cutting process derived from the reflex-percussive method of controlled concrete removal. This method was recognized by the Concrete Society of Great Britain in 1972 and was first employed to obtain a rough finish on the pavement. (The cutting process to provide the "reflex-percussive grooves" is patented by a Canadian manufacturer.) Performance results of these grooves on portland cement concrete (pcc) are detailed elsewhere.[5] Although still in the experimental stage, the reflex-percussive grooves offer a cost-competitive alternative to the square saw-cut grooves. The reflex-percussive grooves could be installed in two orientations because the cross section of the grooves is nonsymmetrical. Depending upon the direction of travel, the tire will encounter different flow conditions as it hits the groove. In an attempt to isolate preferred orientation of the grooves in terms of improved braking performance for one orientation over the other, it was found in an earlier investigation[5] that the braking performance was comparable for both orientations; however, the orientation shown in Fig. 5 was chosen for further investigation because of lower accumulation of rubber on this orientation.

Low-cost groove pattern can also be provided by increasing the spacing of the saw-cut grooves.[6] Therefore, the program included saw-cut grooves spaced between 1¼ and 3 in. A few runways with saw-cut grooves spaced 3-4 in. can be found in the United States and Europe.[7]

Test Parameters

Table 1 lists a summary of the test parameters employed in the program.

Test Procedure

1) Desired wetness was achieved in the test sections.

2) Operational parameters were set on the jet vehicle and tire-wheel assembly.

3) Jet vehicle and assembly were released from the launch end.

4) Jet vehicle was braked and separated when the desired test speed was achieved.

5) Tire-wheel assembly entered the test sections.

Discussion of Results

Before discussing the results, it may be worthwhile to explain the relationships among some of the parameters of the interface. The improved braking action of an aircraft tire on a grooved runway is the result of a dual process of water removal from the tire-runway interface. First, the grooves influence the surface water drainage (runoff) by providing channels through which water can flow freely. Second, the grooves provide forced water escape from the tire-runway interface when the aircraft travels on a water-covered runway. Both the free flow and the forced flow are important, because together they comprise the total flow. Groove roughness and spacing

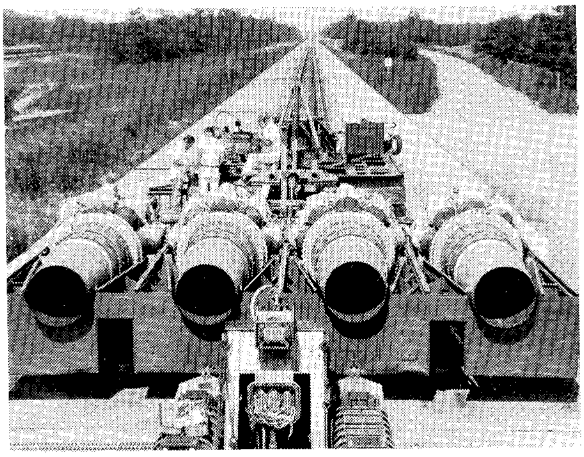
Fig. 1 Jet-powered vehicle and associated system.

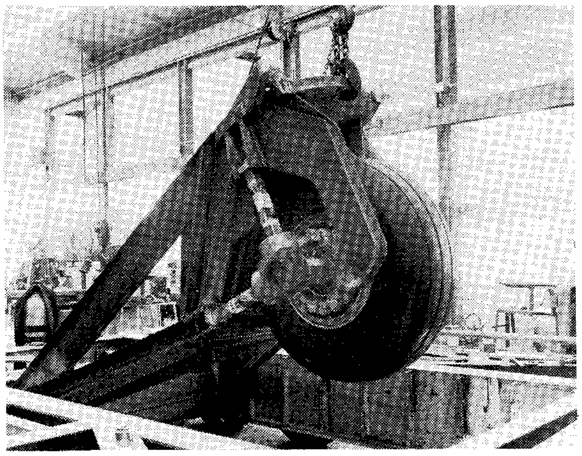
Fig. 2 Tire-wheel assembly.

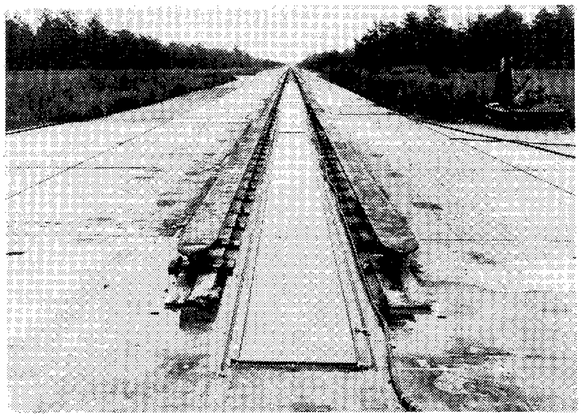
Fig. 3 Test bed at the end of the track.

Table 1 Test parameters

Tire parameters	
Vertical load	35,000 lb
Inflation pressure	140 lbf/in.^{2}
Tread design	Worn tire
Size/type	49 × 17, 26-ply, type VII
Surface parameters	
Type	Asphaltic concrete
Texture	0.014-in. nongrooved
Treatment	Square saw-cut grooves of ¼-in. size with spacing 1¼-3 in., V grooves with 20-deg groove angle and 3 in. spacing, and porous friction overlay with ½ in. maximum size aggregate.
Environmental parameters	
Wetness or water depth	0.01 in. (wet) 0.10 in. (puddled) 0.25 in. (flooded)
Operational parameters	
Wheel operation	Rolling to braked
Brake pressure	200-2500 lbf/in.^{2}
Antiskid system	Not operative
Speeds	70-150 knots

play important roles in determining the flow of water out of the interface. Being laminar in nature, the free flow is enhanced if the groove channels are smooth, while the forced water escape is essentially turbulent and requires rough groove channels to provide a shallow velocity profile for increased flow. The free flow, however, may also be turbulent during rain because of the mixing of the pelting rain. An increase in the number of escape paths, resulting from closely spaced grooves, promotes water runoff[8]; however, since at higher aircraft operating speeds the time available for water to escape from the interface is reduced, the amount of water that can be expelled from the interface is limited by inertia of water.

Thus, the optimum removal of water from the aircraft path on the runway results from a complex relationship between groove roughness, groove spacing, and tire speed.

Braking Action

A wet surface represents a condition encountered during or after a light rain. Puddled and flooded surfaces are representative of conditions prevailing immediately after heavy rains of short or long duration, respectively. When nongrooved, the wet surface provides adequate braking action to a worn tire (Fig. 6); however, installation of grooves in the surface or application of a porous friction overlay improves the braking action significantly, as shown in Fig. 6. Figure 7 shows the results on a flooded surface containing all of the treatments. In each case, incipient hydroplaning is delayed beyond 150 knots. All of the treatments provide similar braking action as represented by a single curve. The braking action on a puddled surface is shown in Fig. 8. The sensitivity of the friction coefficient to the spacing of square saw-cut grooves is obvious: 1¼-in. spacing provides the highest braking action. The reflex-percussive grooves provide braking action equivalent to saw-cut grooves spaced between 2 and 3 in.

A comparison of all of the surface treatments under various water depth conditions is shown in Fig. 9. The observed behavior can be explained by physical interpretation of the data. Although this research did not include instrumentation to measure the water escape paths or amount of water escaped, an attempt is made to explain how grooves help water escape. When a worn tire travels over a wet surface with grooves, predominantly viscous pressures are developed in the interface; viscous pressures alone are not sufficient to lift the tire off the ground. Because only a small amount of water is present in the interface, most of it is expelled through grooves and all of the surfaces provide high friction levels, as shown by the curve marked "wet" in Fig. 9.

When the grooved surfaces are puddled, hydrodynamic pressures become important. The additional water in the interface must be removed to reduce the buildup of hydrodynamic pressures to ensure contact between the tire and runway.

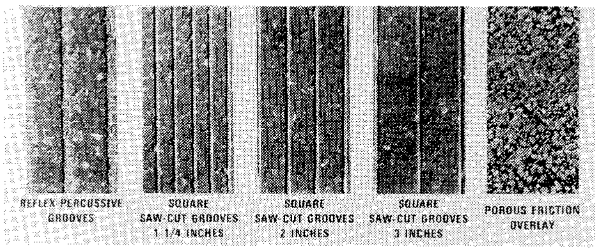

Fig. 4 Various surface treatments.

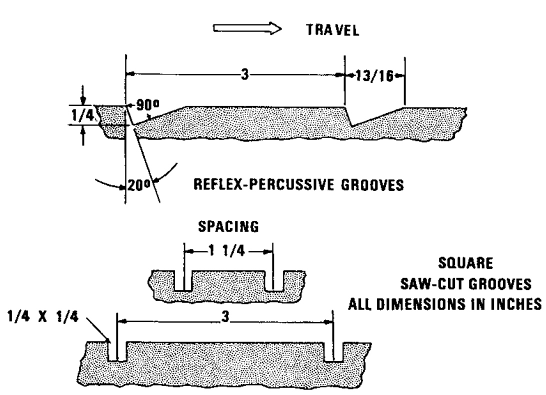

Fig. 5 Groove dimensions.

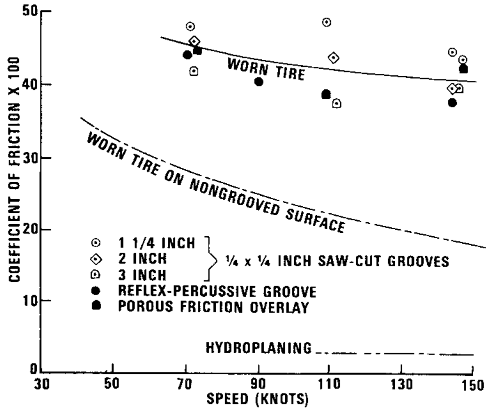

Fig. 6 Braking performance of a worn tire on a wet surface.

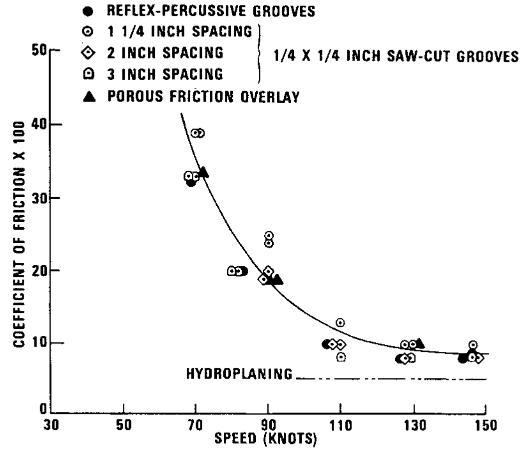

Fig. 7 Braking performance of a worn tire on a flooded surface.

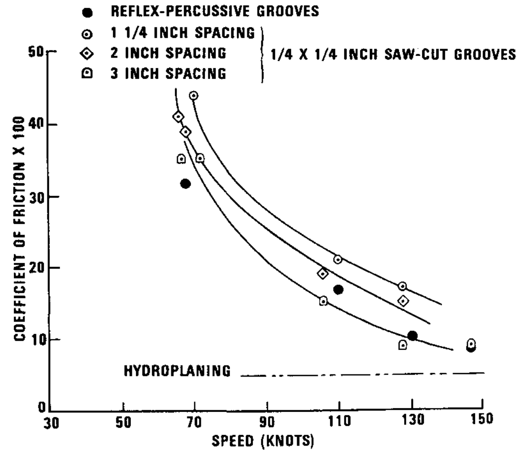

Fig. 8 Braking performance of a worn tire on a puddled surface.

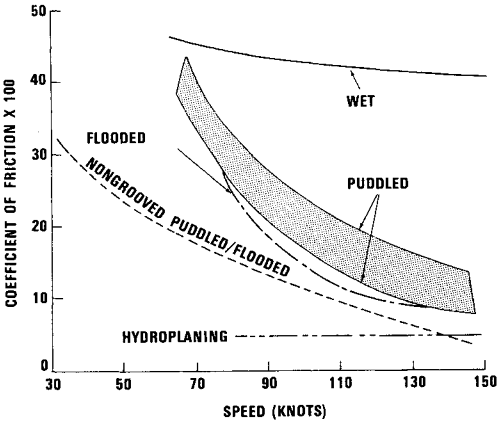

Fig. 9 Comparison of all surface treatments under wet, puddled, and flooded conditions (data point removed).

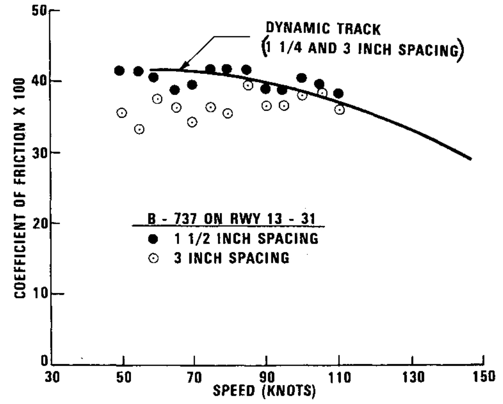

Fig. 10 Braking performance of an aircraft on a grooved runway.

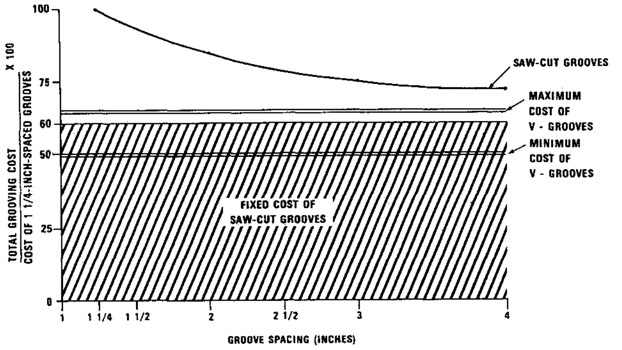

Fig. 11 Estimated grooving cost as a function of groove spacing.

When the grooves are spaced more closely, water particles trying to escape through the rear of the contact wall will find it easier to escape through the grooves and develop a "drier" interface. However, a very large spacing will be ineffective in forcing the water out of the interface because it simulates a nongrooved surface and the friction coefficient will approach hydroplaning level, as shown in Fig. 9. An optimum condition would be when all of the water is expelled from the interface in such a way that the water-carrying capacity of the grooves is fully exhausted. This condition could be obtained by a certain combination of groove spacing and amount of water on the runway surface. Thus, for the wetness for which groove capacity of 3-in.-spaced grooves is exhausted, the capacity of 1¼-in.-spaced grooves will not and these grooves will provide a "drier" contact. The results on the puddled surfaces with grooves verify this phenomenon; the shaded area shows the extent of the water-carrying capacity as a function of groove spacing; the top boundary represents the 1¼-in.-spaced grooves; and the bottom boundary represents the grooves spaced at 3 in.

When the grooved surfaces are flooded, the available friction levels are insensitive to grove spacing. The dotted curve below the shaded area represents results on all surface treatments. For the flooded surfaces, the grooves are filled with water even before the tires pass over them. Then, the inertia of the water particles retards the escape of water in all directions when the tires do travel over the surfaces. The reflex-percussive grooves and the porous friction overlay perform alike under wet and flooded conditions. The breaking action is equivalent to square saw-cut grooves spaced at 3 in.

Aircraft Tests on a Grooved Runway

A joint FAA/NASA test program, currently under way, includes testing with a NASA Boeing 737 airplane. The testing is being conducted at the NASA Wallops Test Facility and the FAA Technical Center runway 13-31. The 10,000-ft runway at the Technical Center has a unique grooving configuration ideal for full-scale testing: it includes square saw-cut grooves at 1½ and 3 in. and small nongrooved sections. A direct performance comparison of the grooves is possible. Preliminary results from the joint program on runway 13-31 are shown in Fig. 10. Superimposed on the aircraft data points is a curve showing the results from the jet vehicle track test[9]; track tests were conducted on grooves spaced 1¼ and 3 in. in the speed range of 70-150 knots. It can be seen that the performance of square saw-cut grooves spaced between 1¼ and 3 in. is similar in the speed range of 90-110 knots.

Cost Comparison

The cost of square saw-cut grooves is influenced by groove spacing. Study[6] shows that the fixed and variable construction costs for grooving the runways are 60 and 40% respectively, of the total cost. The study also shows that the variable cost of the grooving is continuously decreased as the groove spacing is increased; ultimately, the total cost would approach fixed cost if only one groove were to be installed on the runway. Figure 11 shows the relative cost savings as a result of increased spacing of the square saw-cut grooves or the installation of reflex-percussive grooves. The latter offers a viable cost-competitive alternative to saw-cut grooves; however, cost estimates and full savings potential can only be affirmed after application of these grooves in an operational environment.

Conclusions

The following conclusions are drawn from the findings of this research. These conclusions are valid for the operational parameters included in the study.

1) High-speed braking tests show that low-cost surface treatments can be provided either by increasing the spacing of the square saw-cut grooves beyond 1¼ in. or by installing the V-shaped grooves using a reflex-percussive cutting process.

2) When predominantly puddled water conditions are encountered on a runway surface, the closely spaced saw-cut grooves are preferable, although all treatments included in the test program will delay aircraft hydroplaning beyond 150 knots.

3) Selection of a particular treatment on a runway can be based on seasonal rainfall conditions and the cost of installation of the treatment.

4) Under all conditions of operation, square saw-cut grooves spaced at 1¼ in. provide maximum braking action to an aircraft tire.

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