Suction Braking

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The concept of suction braking is described and its potential explained. Model experiments applying the concept to ACLS and initial manned aircraft experiments using the Bell converted LA-4 are described. Design problems are discussed. The use of suction braking as the total braking system or as a supplementary system is considered. Effect on field length due to greatly improved deceleration capacity and effect on slippery surface stopping are displayed. In conclusion, the potential gain is related to transport airplane productivity.

Introduction

THE deceleration D available to a wheeled vehicle of weight W in ground contact normally is limited by the friction coefficient μ between tires and ground, i.e., $D=\mu W$, $D/W=\mu$. The deceleration in g's is equal to the friction coefficient, which is normally not much over 1.0 for rubber on dry concrete and sometimes less than 0.1 on wet or slippery surfaces.

More strictly, however, $D=\mu P$, where P is the download, which can be less than the weight if the vehicle has an air upload as in aircraft or more than the weight if it has a download as in horizontal planes in racing cars. Thus, if $P/W=n$, then $D/W=n\mu$.

The use of a vacuum chamber beneath an automobile to increase the "adhesion" between the wheels of the vehicle and the road was proposed by Nicin in 1929[1] (Fig. 1). It was employed with winning effect by a racing car called the Chapparel in 1970. Use of a large suction cup type of device for similarly increasing the tractive engagement between wheels and surface for an airplane tug was disclosed by Gondert and others in 1965[2] (Fig. 2). In these examples, an additional system is required to obtain the increased capability, adding weight, cost, and complexity to realize a feature that usually is needed on only a small percentage of occasions.

In this paper, suction braking is discussed relative to air cushion landing system aircraft. The air cushion landing system aircraft[3] (Fig. 3) already has a bona fide large-suction cup: the air cushion trunk, so that in order to reap the benefit, it is necessary only to evacuate the cushion cavity to subatmospheric pressure, for example, with a jet pump or additional fan(s) for a minimal cost and weight increment. Two factors are particularly important in the aircraft application:

1) Field length is related to stopping distance: in landing, directly, and in takeoff by accelerate-stop distance. Consequently, reducing stopping distance can make smaller airports accessible to large, high-performance aircraft and can increase the safety of flight operations.

2) The air cushion is fundamentally a large-area, low-pressure device. A typical installation for a 100,000-lb aircraft will operate on 2-psi cushion pressure supporting the aircraft. If full vacuum could be applied to this whole area, an 8-g download then would be possible. In practice, the area is reduced by the suction, and only a partial vacuum is possible, but the potential is still very great: greater than in denser vehicles

Model Experiments

Experiments were performed on a small model shown schematically in Fig. 4 and in the photograph of Fig. 5. This model weighed 40 lb and was equipped with a pillow brake system.[4] Figure 4 shows how flow passages were arranged so that the fan inlet could suck the cushion cavity at the same time that it inflated the trunk (superficially a "boot-strap" configuration), or, alternatively, use could be made of a small ejector. The significant results are shown in Fig. 6.

Use of the fan to do both jobs requires an additional available total head rise, which tends toward inefficient operation in the normal mode at one end and fan stall at the other. The fan used on the model increased the braking g's up to about 1.0 on the brink of stall on a surface having $\mu=0.7$. Adding the ejector, however, permitted considerably more suction to be generated, and drag loads considerably more than twice the model weight were achieved.

It also was found that the ventilation of the cushion cavity provided by (and an essential feature of) the brake pillow inflation effectively inhibited the generation of suction within the cushion cavity. It was necessary to release the pillow brakes for the system to work.

Manned Aircraft Experiments

The next step was to reduce the system to practice at "full scale." For this purpose, the Bell Lake LA-4 ACLS con-

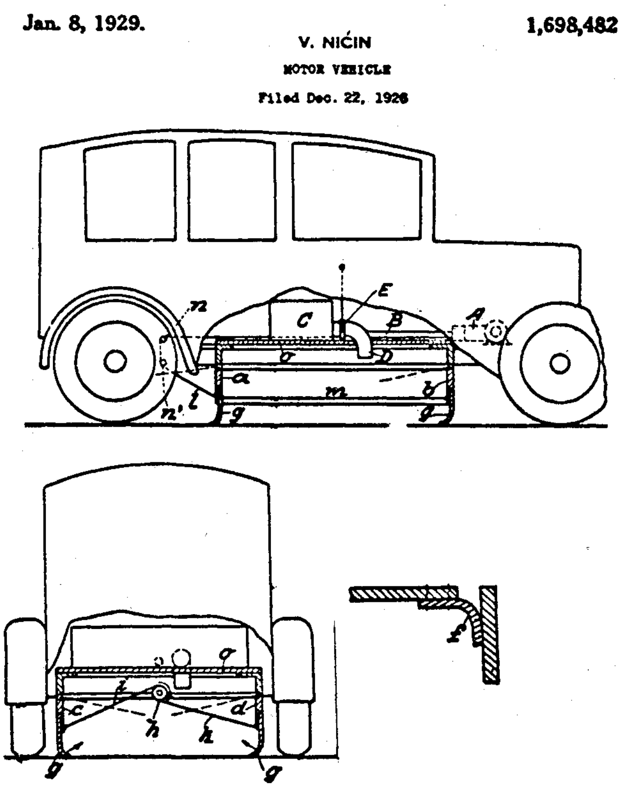

Fig. 1 Device for increasing pressure of wheels on the road.

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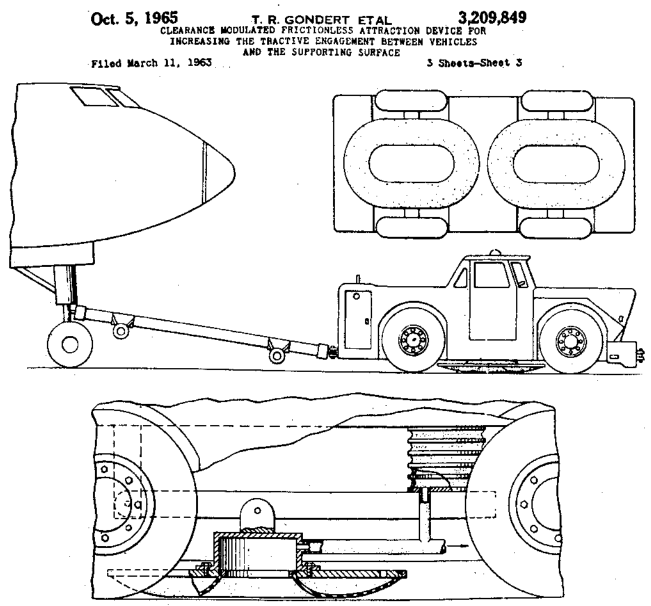

Fig. 2 Device for increasing the tractive engagement between vehicles and the supporting surface.

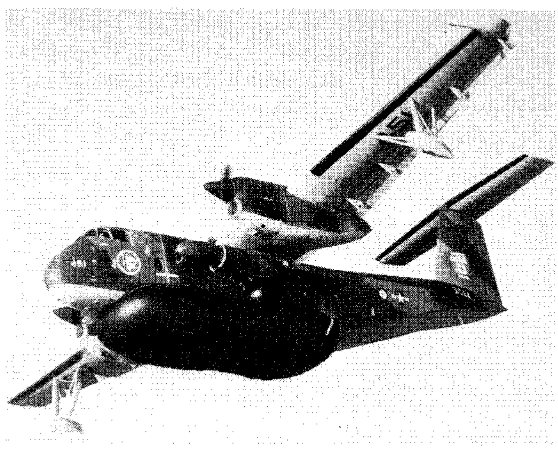

Fig. 3 The XC-8A Buffalo with air cushion inflated in flight.

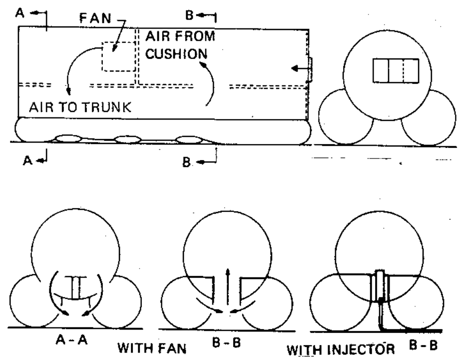

Fig. 4 Schematic of suction braking model.

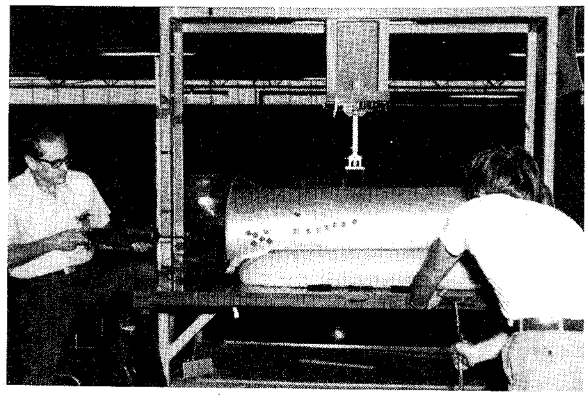

Fig. 5 Suction braking model test.

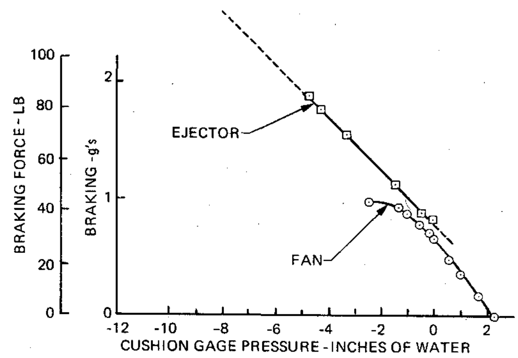

Fig. 6 Suction braking model test results.

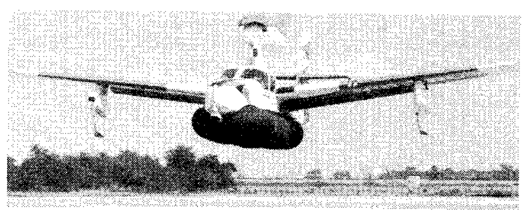

Fig. 7 The Bell LA-4 ACLS conversion.

version (Fig. 7) was adapted for suction braking tests. A new trunk (without pillow brakes) was fitted to the aircraft. Braking skids were adapted for increased area contact, using a single long skid strip on each side. A jet pump was used to evacuate the cushion cavity, powered from stored nitrogen bottles in the cockpit. The jet pump evacuated a plenum in the cockpit connected to the cushion cavity.

Slow-speed runs were made taxiing without brake and using the suction brake to stop. Deceleration was very rapid, stopping from approximately 15 fps in 5 ft. Tests had to be discontinued because of a lift engine failure, but further tests employing a small additional fan instead of the jet pump and providing for measurements of aircraft deceleration, transient air cushion characteristics, etc., are anticipated.

System Design Problems

If the air cushion has a narrow beam as commonly happens if the trunk is installed under the fuselage of a high-wing airplane, suction in the cushion cavity (which pulls the trunk inwards) may reduce the area on which the low pressure acts so radically that the system is ineffective. A wider air cushion is desirable for other reasons also (particularly roll stiffness) so that suction braking is illustrated best in a low-wing airplane, as exampled in Ref. 5. Figure 8 is derived from Fig. 14 of Ref. 5 and shows the conditions based on two-dimensional considerations. The relationship is determined by continuity of tension at the ground tangent.

$$P_j R_1 = (P_j - P_c) R_2, R_1/R_2 = 1 - (P_c/P_j)$$

Where R_1 and R_2 are, respectively, the outboard and inboard radii of the trunk, and P_c and P_j are, respectively, the cushion and trunk pressures. Thus, if cushion pressure is reduced to a negative value, $R_1 > R_2$. The example shown postulates P_c negative equal in magnitude to the normal P_c positive for complete cushionborne support. This results in a trunk deformation, causing a reduction in cushion area to

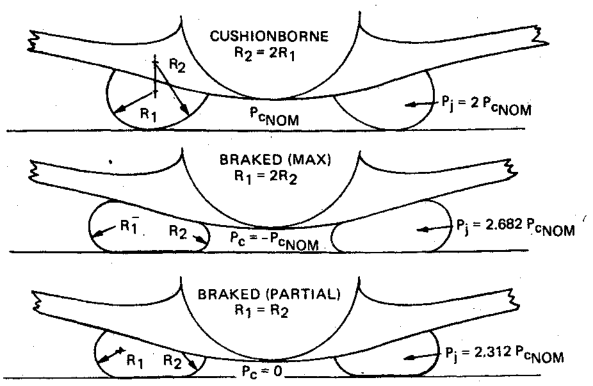

Fig. 8 Comparative cross sections.

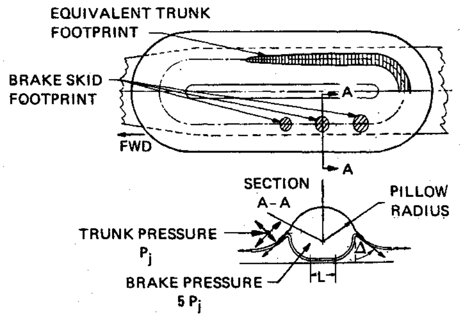

Fig. 9 Equivalent brake system footprint and pillow load mechanism.

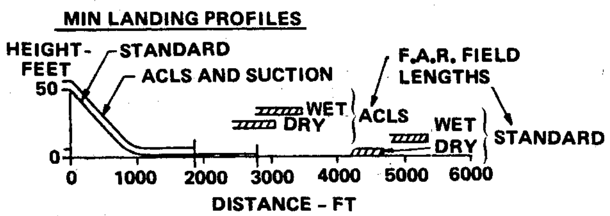

Fig. 10 Comparative field lengths.

about half the normal 1-g area and at the same time a trunk footprint about one-third of the normal beam (ground tangent to ground tangent):

$$P_c = P_{c_{\text{nom}}}, \qquad P_j = 2\,P_{c_{\text{nom}}}$$

$$P_c = -P_{c_{\text{nom}}}, \qquad P_j = 2.68\,P_{c_{\text{nom}}}$$

$$P_c = 0, \qquad P_j = 2.31\,P_{c_{\text{nom}}}$$

This could support a 1.5-g steady vertical force. Trunk pressure is increased because flow is reduced by the trunk flattening. The intermediate case with $P_c = 0$ shows the reduced footprint width with 1-g download. Both braking cases refer to the static condition with no wing lift. Evidently, further increase in suction will cause a further reduction in both of the trunk radii and also ground clearance, with the inner radius decreasing more than the outer. The adverse effect on available suction area is, however, diminishing rapidly.

Because effectiveness depends on generating suction, it is nugatory to pump air into the cushion space, either from the trunk or directly into the cushion, when trying to achieve maxumum braking. However, the trunk flow into the cushion is throttled by the flattening as stated previously and elimination of direct flow into the cushion cavity as part of the suction system can be achieved as is indicated in Ref. 5

The superior braking provided requires a brake skid that will accept a much increased rate of energy dissipation when it is used. In the majority of instances, the full brake power may not be employed (for example, on dry concrete) because the chief advantage is for use on more slippery surfaces. However, it must be capable of meeting requirements for acceptable wear. Acceptable wear is possible because of the very large footprint area that develops at low contact pressure (equal to trunk pressure). This is contrasted with the pillow brake that concentrates wear into smaller areas. Figure 9 taken from Ref. 3 illustrates the equivalence.

Suction braking does not provide for differential action. This feature could be restored on smooth surfaces by providing air lube jets differentially valved. However, for a distributed jet system, complexity in such valving is difficult to avoid, and, moreover, the suction and pillow brake are compatible in operation. Thus, the suction system can be used as the sole system or in combination, possibly using the pillow system for 1) low-speed maneuvering, 2) better braking on rough surfaces, and 3) operation over a surface covered with damaging loose material. The effect of surface roughness is to tend to ventilate the cushion cavity, producing the same effect as pillow inflation, hence making it more difficult to generate suction, whereas loose material is liable to damage the suction device, particularly if it is a fan. Finally, two points must be mentioned:

1) Elastomeric materials although providing the best friction coefficient (rubber on dry concrete), wear very rapidly at interface temperatures exceeding about 300°F, which is reached quickly at high interface pressures. Thus, the order-of-magnitude increase in contact area of the suction system permits use of these materials in larger, faster aircraft.

2) The additional drag loads from the larger braking decelerations are transmitted to the hard structure from the trunk in well-nigh-optimum fashion, mainly involving distributed shear forces into the fuselage.

Field Length Effect

Effect on field length conveniently may be considered in terms of commercial regulations. At the present time, federal regulations do not require full runway condition accountability. This is assumed to be covered by the way landing field length is prescribed for dry runways plus a flat 15% for slippery conditions, if anticipated. The dry runway required is such that the total landing distance over a 50-ft barrier to rest must be accomplished in 60% of its effective length (FAR 121.195). On a twin-engine airplane, rules do not permit reverse thrust to be used in the determination of landing distances [FAR 25.125(f)].

Since the rollout from touchdown to rest is commonly around 60% of the total from 50 ft and touchdown may be, say 300 ft from the beginning of the runway, the wet rollout available divided by the hard dry rollout distance (assuming a field length of the order of 5,000 ft from 50 ft) is 3.07. If the average deceleration on a hard dry surface is 0.307 g, therefore, there will be no runway left if the deceleration is reduced to 0.1 g. In the slippery runway case, reverse thrust will be used; however, if conditions are critical or hydroplaning occurs, the overall margin for error can become small. Although the chief advantage of suction braking is, in reality, for use on slippery runways, since the deceleration achievable is rather extreme for use on dry concrete, nevertheless the reduction in landing field length requirement is determined by performance on the latter surface, without reverse thrust, for the case in point.

Deceleration achievable with suction braking is limited by suction power and the provision of a skid brake that will stand up to it without excessive wear [FAR 25.125b(2)]. In Fig. 8, P_c negative equal in magnitude to the normal 1g P_c positive is treated as maximum. This adds 0.5 g steady download and on dry concrete is expected to add 0.4 g (0.8 friction coefficent) drag. This reduces field length for the Ref. 5 example aircraft by 35%.

It has a similar effect on takeoff field length because of the reduction in accelerate-stop distance. The superbraking favors the abort and is likely to set $V_1 = V_R$ [FAR 25.111a(2); V_1 must be on the ground]. Rapid trunk retraction also reduces the single-engine climb distance to 35-ft altitude, tending to compensate and bring down the balanced field length. The landing profiles are compared in Fig. 10

Productivity Effect

Reduced field length may be credited as a performance advantage, permitting a given airplane having a particular transport efficiency to land in more places. In this case, improved productivity results from improved payload access to final destinations and therefore total system savings. Such savings are equally real for military aircraft, though even more difficult to quantify. A less imponderable method of capitalizing on this feature is to use up the same field length but increase the gross weight or reduce wing area accordingly, thus, in turn, improving the airplane payload and transport efficency.

Sensitivity factors used by NASA in advanced technology transport studies were applied in Ref. 6 to relate brake deceleration to payload in this manner. Approximately 25% payload increment for 0.15 *g* brake increment was reported. If this can be extrapolated, a 0.6 *g* increment could double the payload or halve the fare. In Ref. 7, field length was related similarly to payload and return on investiment. A 30% change in field length was shown to result in a 60% change in payload. These figures indicate that productivity effects are large. The essential point is that the improved braking performance conferred by the ACLS with its suction braking system comes free of a weight increment. It is a net gain.

In terms of fuel used, the expenditure on the ACLS during takeoff and landing is dwarfed by the savings due to reduced gross weight or increased payload. Suction braking greatly enhances the potential of ACLS.

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