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No. 466

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WHEEL BRAKES AND THEIR APPLICATION TO AIRCRAFT

By G. H. Dowty

From "Flight," November 24, and December 29, 1927  
and January 26, 1928

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 466.

WHEEL BRAKES AND THEIR APPLICATION TO AIRCRAFT.

By G. H. Dowty.

Until quite recently wheel brakes have not been seriously considered in connection with aircraft, for their application has generally been regarded as a menace rather than an advantage. Their use has always been associated with a tendency for pitching of the airplane on its nose and, in any case, to give no great advantage when compared with the additional weight and complications consequent to their adoption.

Compared with the motor vehicle, brakes on an airplane have a very restricted use, and are confined to checking the length of run on alighting and subsequent operations on the ground.

It must be admitted that the airplane exists under a considerable handicap, in that it requires a greater space within which to arrive and depart than any other means of transportation. The airplane is the only vehicle used which does not apply brakes on stopping, and yet it is the one mostly in need of braking, since its speed is the greatest.

The advantages to be gained from braking have not been ignored, and in the search for a suitable method many schemes have been suggested and tried. The following have been some of the most popular methods to receive attention:

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\*From "Flight," Nov. 24 & Dec. 29, 1927, and Jan. 26, 1928.

- 1) Increasing the height of the landing gear to produce a large angle with the ground;
- 2) Air brakes of various forms such as expanding rudders and flaps;
- 3) Sprags on tail skid and axle;
- 4) Wheel brakes.

The first method, while satisfactory, is necessarily limited, and has the further objection that it is not positive.

Air brakes have been repeatedly tried, but have always been discarded because of their almost negligible effect at low speeds.

Provision of sprags on the tail skid has the disadvantage of setting up heavy loads in the fuselage and, furthermore, their use is to be deprecated owing to the excess damage caused to the landing ground.

Wheel brakes are the subject of this paper. Their use on aircraft is not new, for many forms of this type of brake have been tried out. Generally, such brakes have been fitted in conjunction with a leading wheel or skid to prevent the airplane turning over. The recent popularity of braking has been chiefly due to the requirements of shipboard landings and a general tightening up of aircraft specifications.

It has been suggested that reversing the propeller would meet the requirements of a suitable brake, but the mechanical difficulties have not, as yet, been overcome. With the advent of the variable pitch propeller this may be possible, but this form

of braking would not be effective with the engine stopped.

The use of slotted or variable camber wings will, in a great measure, achieve the object of minimizing the space required for taking off and alighting, but over and above this feature there always remains the question of maneuverability on the ground. In some cases the pilot can obtain a certain amount of directional control by a burst of engine, and the slip stream effect produced thereby, but in many cases, particularly in deck work, this may not be possible.

It is not unusual for a large personnel to be required to assist handling of airplanes, and it is here that independently operated wheel brakes can be of value in simplifying ground work and reducing the number of ground staff to a minimum.

Recent developments, particularly in America, have demonstrated the value of aircraft wheel brakes, and proof is given from the figures of the recent American National Air Tour. The figure of merit for determining the winning airplane of this competition was based on the formula

$$\frac{W \times V_{\max} \times 50}{C(T_s + T_{us})}$$

where

W = useful load (lb.)  
V<sub>max</sub> = maximum flying speed (M.P.H.)  
C = engine capacity (cu.in.)  
T<sub>s</sub> = time to "stick" (sec.)  
T<sub>us</sub> = time to "unstick" (sec.).

The high value attached to quickness of pull-up, or time to "stick," is apparent, and it is therefore not a matter of surprise to find that of thirteen airplanes starting, ten were equipped with wheel brakes. Of the eleven airplanes to complete the competition the first places were all occupied by airplanes fitted with these brakes.

The promoters of the Guggenheim Safe Aircraft Competition attach such great importance to the ability of an airplane to pull up quickly that they have allocated over half the total number of points to be awarded for these tests. Out of a total of 200 points, 40 points are given to an airplane coming to rest, in calm air, in 40 ft. after touching the ground, and a further 75 points are awarded for the ability of an airplane to come to rest, in calm air, 150 ft. from a 35-foot obstruction. It would therefore seem desirable, if not essential, for competing airplanes to be equipped with wheel brakes.

High-performance aircraft for deck landing will benefit by braking owing to the very limited length of run available. Land airplanes will possibly find an advantage due to the very fine steering qualities provided by the brakes and by the possible elimination of wheel chocks for the preliminary starting and running up of the engine. In this connection, wheel brakes should make a strong appeal to the light airplane owner, who would appreciate the additional advantages on occasions when assistance was not available.

The fitting of wheel brakes necessitates careful consideration for its effect on general design conditions. It will be found that provision must be made to take the torque reaction of the brakes, and that a revised landing gear structure is necessary. The more or less orthodox type of landing gear, comprising Oleo Leg, Axle, Radius Rod and Cross Bracing, is not, in itself, a suitable structure for taking the torque reaction.

Figure 1 shows a typical landing gear joint where the radius rod is universally mounted to the axle fitting. If this axle was subject to torsion, the whole of the reaction would be taken in bending by the oleo leg. This is not permissible because the leg is composed of telescopic members, and excessive bending would prevent the leg from functioning. This snag could be partly overcome by the substitution of telescopic tubes of larger diameter and gauge, but there always remains the objectionable feature of heavy and clumsy fittings for transmitting the loads from the axle, and the increased frontal area, in the slip stream, due to the greater diameter of leg. There is an alternative scheme for mounting the oleo leg on a universal joint, thereby ridding that member of bending, and taking the torque reaction in bending on the radius rod. Such a scheme necessitates the radius rod being built integral with the axle, and while this method may appear tolerably good for taking the vertical loads and torque reactions, yet under side loading, the stresses set up will be very great. If we consider any stretch in the cross

bracing wires, then the loads become of a somewhat indeterminate nature, because the axle and radius rods form the sides of a frame having rigid joints. It would appear that the usual type of landing gear structure is not suitable for carrying wheel brakes, and neither does it lend itself to easy adaptation.

There are several types of landing gear structures suited for taking brake loads, and these have been developed to a large extent in America, where wheel brakes are becoming normal equipment. Figure 2 shows a type of landing gear used on the Hamilton monoplane. This consists of a sprung member and two axles which form a pylon with apex at the wheel hub. The axles are socketed in a "Y" fitting and their respective ends are pinned to the under side of the body on the center line of the airplane. The large distance between the body fittings makes for a good base, with adequate provision for taking the torque reaction. A type of structure suitable for a biplane is illustrated in Figure 3. This consists of a sprung member and two axles socketed together, as depicted in the plan view. The ends of the axles are attached to separate pylon structures and pivoted on the center line of the airplane. On both the landing gears shown in Figures 2 and 3, the wheel track outwards, and this may be cited as a disadvantage, in view of the tendency for the tires to rip from the rims. If due care is taken in the design to make provision for greater vertical rise than the corresponding movement outwards, then there need be no fear of any such trouble arising.

The types of landing gear structure shown in Figures 2 and 3 have a most desirable feature, which should make an appeal to those concerned with the design of deck-landing aircraft. It is difficult to avoid one-wheel landings on board ship, due to rolling of the deck, and with the type of landing gear, using a radius rod, the wheel touching the deck first will move ahead, so that when the other wheel makes contact there will be considerable difference in their longitudinal positions. This condition is shown in Figure 4, and must produce racking of the structure and directional instability. These disadvantages are completely overcome in the two schemes shown above, for the wheels have no fore and aft movement.

The foregoing remarks will serve to indicate the nature of the modifications to the aircraft structure that are desirable in order that wheel brakes may be incorporated.

The following will deal with the effect of braking, and show to what limits it can be taken with safety.

There is possibly no other vehicle where the effect of braking calls for a more careful study. The possibility of an airplane nosing over is a primary consideration in the effect of braking, but it will be shown that if care is taken in positioning the wheels, then the possibility of nosing over can be practically eliminated.

The worst case will occur in a tail-up landing, although it is not suggested that the brakes will be normally applied when an airplane is in this position. Yet, in order that every contingency may be covered, the tail-up case must be taken, and

will provide the conditions governing maximum permissible braking. This statement may be criticised in view of various systems for brake operation from the tail skid, but when control systems are discussed at a later stage more detailed reference will be made to this method of operation.

Figure 5 shows a side elevation of an airplane.

Let  $fW$  = load borne by wheels,

$R_1$  = distance of wheel ahead of c.g.,

$R_2$  = distance of c.g. above ground,

$\mu$  = coefficient friction between tire and ground.

The maximum brake load is given by  $\mu f W$ , and consequently, upon application of the brake load, there is a pitching couple of value  $\mu f W R_2$ , and a counteracting couple of  $f W R_1$ . In order that the airplane may not nose over

$$f W R_1 > \mu f W R_2.$$

The limiting value of  $\mu$  is therefore:

$$\mu = \tan \alpha.$$

This angle is usually between  $12^\circ$  and  $13^\circ$ , on normal landing gears, but where wheel brakes are fitted, American practice is to increase this angle to  $17^\circ$ .

In order that the value of braking may be appreciated, the tangents of angles  $12^\circ$  to  $17^\circ$  are given below:

$\alpha$	$12^\circ$	$13^\circ$	$14^\circ$	$15^\circ$	$16^\circ$	$17^\circ$
$\tan \alpha$	0.212	0.230	0.249	0.267	0.286	0.305

A disadvantage may be found in placing the wheel forward, in view of increased tail loads, but  $17^\circ$  has been found to be a sound compromise, permitting of excellent braking.

In a tail-down landing angle  $\alpha$  will be increased by angle  $\beta$ . Angle  $\beta$  is usually about  $13^\circ$ , and the braking can be considerably increased.

$\alpha + \beta$	$24^\circ$	$25^\circ$	$26^\circ$	$27^\circ$	$28^\circ$	$29^\circ$	$30^\circ$
$\tan(\alpha + \beta)$	0.445	0.466	0.487	0.509	0.532	0.554	0.577

In the case of an airplane with wheels disposed such that angle  $\alpha$  is  $17^\circ$ , then the wheels may be locked and a safe tail-up landing made, providing the coefficient of friction between tire and ground does not exceed 0.3. If the more usual three-point landing is made then, under similar conditions, the coefficient can reach 0.5 with safety.

These statements are borne out by actual tests\* which have shown that, with a well-proportioned landing gear, the wheels may be locked and the airplane landed without difficulty.

#### Coefficient of Friction

In the whole question of brake design there is, perhaps, no more arbitrary point than the coefficient of friction between tire and ground. This is unfortunate because it is the datum line from which brake design starts. The coefficient varies between wide limits depending upon the nature and conditions of

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\*"Airplane brakes," by Weaver, "Slipstream," Nov., 1927.

the surface, inflation pressure of the tires and type of tread. If the tires are very soft and the surface uneven, then it has been found that coefficients of friction in excess of unity can be obtained, due to interlocking of the tire with the interstices of the ground. For any given tire, increase of inflation pressure produces a slight improvement on the braking effect, since the area of contact is reduced and the pressure per unit area increased.

In a paper dealing with four-wheel brakes and read before the Institution of Automotive Engineers, Mr. F. A. Stepney Acres has shown that over a series of tests on road surfaces, the coefficient varies between 0.46 and 1.3, with an average value of 0.7.

Inquiries from the Dunlop Rubber Company, produced the following information:

Coefficient Friction between Tires and Various Surfaces

Surface	Condition	$\mu$	Authority
Granite setts	greasy	0.2	Dunlop Rubber Co.
Macadam	dry	0.7	" " "
Steel (smooth)	wet	0.1	" " "
Steel (smooth)	dry	0.6	" " "

It will be noticed that the coefficient of friction between a rubber tread and ordinary types of road surface may vary from less than 0.02 to 0.7. In view of landings on steel decks, the coefficients of friction between rubber and steel surfaces are of interest. Upon a wetted steel surface the coefficient is

very low, and of the order of 0.1, but the deck of an aircraft carrier is not perfectly smooth, and is slightly roughened by the application of a cement coating. There are no actual figures available for the coefficient of friction on such a surface, but they will be appreciably higher and approximately of the order of 0.7.

Unfortunately there is, to the writer's knowledge, no reliable data concerning the coefficient of friction between aero tires and landing fields, but from values deduced from actual landing tests, the coefficient appears to be quite small, particularly so on wet surfaces.

The only information obtainable refers to tests on automobile tires and we can assume that, for aero tires with smooth treads, these values will be reduced. From comparison of tires with smooth and patterned treads, it appears that the coefficient of the former is about 0.8 of the patterned (non-skid) type. The maximum coefficient for aircraft tires probably lies in the neighborhood of 0.5 with a mean value under normal conditions of 0.25.

From previous considerations of the maximum braking permissible, it will be seen that even in the unlikely event of the wheels becoming locked, a tail-down landing can be made with absolute safety under the worst conditions and a tail-up landing under normal conditions. It has been definitely proved, by actual tests, that wheel brakes are perfectly safe in operation.

Throughout the whole of the preceding work, no reference has been made to aerodynamic resistance. This drag will have the effect of permitting an increase in the brake load, with a consequent reduction in length of run. At speeds below 40 M.P.H. the drag falls off very rapidly and its effect is small compared with the braking produced by the wheels. It has been thought desirable to ignore this drag in view of the additional complications that would be involved by its inclusion.

The magnitude of the braking load is only of interest in so far as the actual brake design and length of run is concerned. The maximum brake load obtainable is equal to the weight borne by the wheels and multiplied by the coefficient of friction between the wheels and landing ground. The weight borne by the wheels has to be determined by subtracting from the total airplane weight, that part carried by the air at any instant plus that part carried by the tail skid.

The actual process for determining the weight borne by the air, is quite simple, but the lift experienced will be subject to large variations depending on the attitude of the airplane during landing. The extreme cases will be represented in a tail-up and a tail-down landing. Typical values for the lift, in terms of total airplane weight, are given in Figures 6 and 7. When the airplane is in any intermediate position, the lift will range between these two sets of values. The results given in the above figures have been obtained from analysis of a partic-

ular airplane and will serve to indicate the order of loads that may be expected. The excess of weight over lift represents the wheel load and this has been plotted on Figures 6 and 7. Tail skid loads, being of a small order, have been ignored in the tail-down case. Wheel loads have been obtained on the assumption that the airplane has been rolling over a smooth surface and not subject to inertia loading.

During the initial stages of alighting, wheel loads will be of a higher order, depending essentially on the vertical velocity of the airplane and the vertical travel of the wheel.

If we consider the total weight of the aircraft to be air borne, then the wheel load ( $f/W$ ) can be determined from:

$$\frac{f}{W} = \frac{V^2}{2g T} = \frac{0.0155 V^2}{T}$$

where  $T$  is the vertical wheel travel in feet. If none of the airplane's weight is air borne, then

$$\frac{f}{W} = 1 + \frac{(.0155 V^2)}{T}$$

The values given by the latter equation have been plotted on Figure 8. The actual wheel loads will vary between the figures given by these two methods, depending on the proportion of the total weight carried by the air.

In the case of shipboard landings where the deck is free from obstructions, the order of wheel loads during run to pull-up, should approximate more nearly to those values given on

Figures 6 and 7, while on turf or macadam surfaces, the increase in loads will depend on the roughness of the surface and the forward speed of the airplane. Some authorities assert that, on average landing grounds, loads up to three times the static load can be experienced during taxiing, but with well-designed shock-absorbing units such as present-day airplanes are normally equipped, the maximum load should not exceed twice the static load and with an average value of 1.1. These figures are confirmed by N.A.C.A. Report No. 249\*, which shows that under normal landing conditions the maximum load does not exceed 2g with a mean value, during run to pull-up, of 1g. These results have been obtained by use of the N.A.C.A. accelerometer and the graphical record of the load alternations is of considerable interest.

The reduction in length of run obtained by the use of wheel brakes cannot be treated in a simple manner. The actual process of calculating the run to pull up, is one of considerable complexity and with many variables entering into the problem. The experience and judgment of the pilot plays a major part in the length of run taken and since this human factor cannot be calculated, it is proposed to consider the retardation of an airplane in as simple a manner as possible. The writer believes that the rather large assumptions made, will possibly provide no greater error than those involved in the more complex investigations.

For general comparative purposes we can take the data given in N.A.C.A. Report No. 249. This gives particulars of length of

\* "A Comparison of the Take-Off and Landing Characteristics of a Number of a Number of Service Airplanes," by Thomas Carroll, (1927)

run and landing speed for nine different types. These figures are given in Table I. Columns 1, 2, 3 and 4 are self-explanatory and in column 5 the average over-all retarding coefficient has been determined.

Table I.

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9
Airplane	Landing speed (V) M.P.H.	Length of run (T <sub>1</sub> ) ft.	V <sup>2</sup>	$\frac{.0334 V^2}{T_1}$	RA	RA + μ	$\frac{.0334 V^2}{RA + \mu} = T_2$	% reduction in length of run
S.E.5a	54	450	2900	.215	.055	.355	272	39.6
J.N.6H Curtiss	51	575	2600	.151	.047	.348	250	56.5
Spad VII	58	485	3360	.232	.072	.372	300	38.2
VE-7 Vought	51	800	2600	.109	.047	.348	250	69.0
DH-4B	56.5	725	3200	.147	.064	.364	294	59.5
CO.4 Fokker	56	950	3140	.11	.062	.362	290	69.5
Sperry Messenger	44	400	1940	.162	.035	.335	193	52.0
M.B.3 Thos. Morse	57	875	3250	.124	.068	.368	295	66.4
M.B.2 Martin Bomber	58	925	3360	.122	.072	.372	302	65.0

From analysis of several types of airplanes, in tail-down attitude, mean aerodynamic drag coefficients have been calculated for various initial landing speeds. The results are given on Figure 9.

The average aerodynamic drag coefficients taken from this figure are given in column 6.

In order that we can forecast the diminution in length of run, by the application of wheel brakes, we can assume the nominal value of 0.3 as representing the coefficient of friction between the wheels (with tail skid) and ground. The total overall retardation coefficient is given in column 7 and the new length of run in column 8. The percentage reduction in length of run, due to the application of wheel brakes, is estimated, under this method, as 57.3. The benefit to be derived from wheel braking is fully demonstrated and the advantages are sufficiently great for efficient braking to be regarded as one of the essential qualities in airplane performance.

Reports of the Boeing Air Mail airplanes say that action of the wheel brakes is astounding and the steering qualities so remarkable that a pilot is able to negotiate his way between obstructions with the ease of a motor car. Besides the advantages to be gained from quickness of pull-up, many accidents occur through poor controllability on the ground, which could be obviated by suitable brake equipment. Airplane wheel brakes are being developed in several countries at the present time and aero wheels complete with brake drums are already in the course of manufacture in this country.

Although much can be learned from automobile practice in wheel brake design and construction, yet the requirements of

aircraft brakes are, in many ways, dissimilar. The following are some of the chief differences that should be noted:

#### Automobile Brake Requirements

1. Equal application of braking on all braked wheels.
2. Ability to absorb power for long periods.
3. Adequate provision for cooling brake drums.
4. Braking demanded at frequent intervals.
5. Provision for renewal of liners.
6. Brake drums generally mounted external or partly external to wheel.
7. Operation of brakes from one control.

#### Aircraft Brake Requirements

1. Independent operation to each wheel for provision of steering.
2. The longest period of braking will not exceed 20-30 seconds.
3. The temperature increase will not be great during the short period of operation, and cooling is of smaller importance.
4. Braking only required during limited period of ground operation.
5. This is not absolutely essential due to the restricted use of brakes.
6. Brake drums must be within the wheel or enclosed by rim to hub fairing.
7. Each wheel must be braked from a separate control.
8. Weight must be reduced to a minimum consistent with adequate rigidity. This can best be obtained by the use of light aluminum alloys.

Essential features common to both classes of brakes are:

1. Self-balancing, i.e., elimination of unbalanced forces when brake application takes place.
2. The brake should preferably be self-energizing.
3. The complete brake system should be exceptionally rigid to withstand vibration and distortion, both being primary causes of brake inefficiency.

### Forms of Brake

Braking members generally used may be divided into two classes, each of these depending upon the property of frictional adhesion between surfaces held in contact by considerable pressure.

The usual construction is the attachment of a pressed steel drum to the wheels and the retarding effect can be produced by an internal expanding shoe or by an external contracting band.

The internal expanding shoe brake is more popular on automobiles, possibly due to its neater arrangement and better facilities for cooling. It would appear that this type of brake is the better one for aircraft purposes. The whole unit can be totally enclosed within the wheel, thereby gaining protection against oil, dust, etc., and the operating means can also be enclosed. The band brake has little to recommend it except cheapness, and perhaps a slight saving in weight. Against this there is the great disadvantage of the cumulative action of the brake, the band tending to wrap itself round the drum with ever-increasing tightness. While this may be tolerated on an automo-

bile, it must not be permitted on an airplane wheel. With some forms of internal expanding shoes this cumulative action can be obtained, but discussion of this point will be deferred.

### Brake Linings

The coefficient of friction of Ferodo fiber or bonded asbestos Ferodo is not appreciably affected by temperature, pressure, or speed. For a temperature of 200°C, pressure 100 lb. per sq.in. and a speed of 6000 ft. per min., there is no diminution of the value below 0.3. The work absorbed by a Ferodo lining varies from 100,000 to 120,000 ft. lb. per sq.in. per min., when  $\mu = 0.3$ , and the pressure varies from 50-80 lb. per sq.in.

Standard automobile practice is to design on 30 lb. per sq.in. pressure for brake linings under normal load.

The following table gives the coefficient of friction for brake linings. This information has been taken from the Practical Engineer Handbook.

It will be noticed that the effect of lubrication is to reduce the efficiency of the brake, and care should therefore be taken to see that the brake is not exposed to oil from the engine. Preferably the complete brake unit should be enclosed. Dissipation of heat is not so important as in automobile work, and advantage can be taken of this point and the brake placed within the wheel.

Surfaces in contact	Condition	$\mu$
Ferodo fiber on metal	dry	0.4 - 0.8
" " " "	oiled	0.05 - 0.1
Bonded asbestos Ferodo on metal	dry	0.3
Bonded asbestos Ferodo on metal	oiled	0.035

The brake lining should be riveted to the shoes with copper rivets. The use of aluminum rivets is to be deprecated because the rivets are liable to harden, become embrittled and break off.

#### S h o e s

It is customary to make the width of brake shoes from 0.1 to 0.15 times the drum diameter, but the width should not exceed a maximum of 3 inches. If the shoes are made of greater width, there is difficulty in securing uniform contact over the entire surface, and this will lead to the concentration of pressure on a small part of the liner.

Brake shoes are usually made from aluminum on the score of weight and the good conductivity of that metal.

#### Arc of Contact

There is evidently a great diversity of opinion regarding the included arc of contact of brake shoes with the drum. In various designs the writer has observed variations between 80°

and  $140^{\circ}$ . There is possibly no advantage to be gained in extending the arc beyond  $90^{\circ}$ , especially if the centers of the shoes are diametrically opposite each other (see Fig. 10), because any increase beyond that has little effect on the retarding power and, consequently, this is adding useless weight. Furthermore, too great an extent of brake lining, particularly in the direction of the operating cams, is undoubtedly the cause of brake chatter. In such cases operation of the brake tends to spring the shoe outward and to give rise to undue pressure at the extremities of the lining.

#### Brake Drums

The drum diameter should be made as large as possible in order that the brake pressure will be reasonably low. This will give the brake a longer life before adjustment is required.

Low working pressure tends to smoothness in action and elimination of squeaks. Squeaking is invariably produced by high-working pressures which cause the brass or bronze wire embedded in the asbestos or Ferodo, to break off into small particles. This results in choking of the brake, necessitating removal of the shoes for cleaning and the possible renewal of brake lining. Increased diameter, besides giving low working pressures, also makes possible a smaller width of drum and this facilitates better streamlining. This point is of considerable importance on aero wheels.

Perhaps the lightest and most rigid form of drum consists of a steel liner on which is shrunk a cast aluminum brake drum. This drum should have circumferential ribs to prevent stretching or distortion. (see Fig. 10). In the case of automobile wheels, the ribs serve the dual purpose of preventing distortion and aiding heat dissipation. It has been definitely established, from automobile tests, that flanged or ribbed brake drums are necessary if spreading of the drum is to be avoided.

The metal liner should be locked to the aluminum drum to prevent its working loose, and this can be provided for by turning a thread on the outer diameter of the liner. This method is shown in Figure 10. The threading should preferably be half left-hand and half right-hand, so that the lock is positive for either port or starboard wheels. Attention to this point will save handing of wheels.

#### Brake Drum Diameter

Using the following notation (see Fig. 11):

$W$  = wheel load (lb.)

$\mu$  = coefficient of friction between tire and ground.

$L_1$  = brake load applied at periphery of wheel (lb.)

$L_2$  = brake load applied at periphery of brake drum (lb.)

$D$  = diameter of tire (in.)

$d$  = width of tire (in.)

$S$  = diameter of brake drum (in.)

$t$  = width of shoe (in.) = 0.1 to 0.15  $S$

$A$  = area of shoe in contact with drum (sq.in.).

$E^{\circ}$  = included arc of contact of both shoes.(degrees).

It has been shown that the average wheel load during run to pull-up is approximately 1.1 times the static load, and  $W$  can therefore be replaced by the term  $1.1 (12 Dd) = 13.2 Dd$ . This is based on the assumption that  $12 Dd$  gives the static load per wheel. Replacing  $\mu$  by the average value 0.3 we get

$$L_1 = \mu W = 3.96 Dd \quad (1)$$

and 
$$L_2 = \frac{3.96 D^2 d}{S} \quad (2)$$

The area of shoe in contact with the drum is given by:

$$A = \frac{\bar{A} S t E^{\circ}}{360} \quad (3)$$

Taking  $E^{\circ}$  (the included arc of contact of both shoes) at  $180^{\circ}$

$$A = 1.57 S t \quad (4)$$

From previous considerations of brake linings it has been observed that the normal working pressure on Ferodo should not exceed 80 lb. per sq.in. and, therefore, from (2) and (4) we can write

$$80 = \frac{3.96 D^2 d}{1.57 S^2 t}$$

i.e., 
$$S^2 = \frac{0.0315 D^2 d}{t} \quad (5)$$

Where  $t = 0.1 S$   $S^3 = 0.31 D^2 d$  (6)

$t = 0.15 S$   $S^3 = 0.21 D^2 d$  (7)

From these formulas the diameters of brake drums for several sizes of wheels have been determined and the results are tabulated below.

Wheel size mm	Equivalent W.O. type in.	Brake drum dia. = "S" in.	
		t = 0.15 S	t = 0.1 S
700 x 75	28 x 3	8	9
700 x 100	28 x 4	9	10
750 x 125	30 x 5	10	11
900 x 200	36 x 8	13	15
1250 x 250	50 x 10	17.5	20
1750 x 300	70 x 12	--	26

#### Self-Balancing

It is a necessary condition that the resultant loads of the brake shoes balance one another. If this point is not given due consideration, then unbalanced forces may develop which are greater than the safe load on the wheel. In any case unbalanced forces are the cause of serious brake troubles, namely, brake chatter, fracture of shoe fulcrum pins and snatching of the operating mechanism

The balance of any brake can be analyzed by finding the center of pressure of each shoe. The center of pressure is that point at which the resultant brake load can be regarded as concentrated. This can be determined in the following manner.

Figure 12 represents a line diagram of a brake unit with  $J$  the brake drum center,  $JA$  the radius of drum,  $X$  the shoe fulcrum, and  $GA$  the arc of contact between shoe and drum.

The arc of contact  $GA$  is divided into several equal parts  $AB, BC, CD, \text{etc.}$ , and each of the points  $A, B, C, D, \dots$  are joined to  $X$  and  $J$ .

Line  $AA'$  is drawn at right angles to  $AX$  and its length is made some definite proportion of  $AX$ . Similarly,  $BB'$  is drawn at right angles to  $BX$  and its length must bear the same relation to  $BX$  that  $AA'$  bears to  $AX$ . This construction is continued for the remaining points.

Line  $A'1$  is now drawn at right angles to  $AJ$  and similar lines  $B'2, C'3, D'4 \dots$  are drawn at right angles to  $BJ, CJ, DJ \dots$  respectively.

Lines  $A1, B2, C3, \dots$  are now resolved into a force polygon and  $AJ$  represents the magnitude and direction of the resultant force.

The position of the center of pressure is found by extending  $AJ$  to cut the arc  $GA$ .

This system is definitely out of balance and the disposition of the components can therefore be regarded as poor.

A layout of a further brake system is shown on Figure 13. The construction of this diagram has been carried out in a similar manner to that described for Figure 12. It will be seen that this system is in balance and the resultants of both shoes are normal to the wheel perpendicular.

The above methods have been fully treated by Mr. Watt.\*

The design of correctly balanced brakes resolves into the location of the fulcrum pins, with reference to the disposition of the arc of shoe contact.

In order that the relation between these points can be readily determined, Figure 14 has been prepared. If the positions given on this figure are adhered to, then complete balance can be assured. It should be understood that the fulcrum pin may be placed at any distance from the drum center, providing the fulcrum is located on the angle stated.

Taking an example from Figure 14: when  $X = 120^\circ$  and  $Y = 80^\circ$  then  $\cos Z = \cos 0.85 = 31^\circ$  approx. The included arc of contact for one shoe is equal to  $X-Z$  and in this case it is approximately  $89^\circ$ .

#### Operating Cams

Cams are generally designed to give progressive brake action, and their form is determined by the travel and the rate of action required. Due to excessive wear on the faces, cams should be mounted with a view to ease of renewal.

#### Disc versus Wire Wheels

It would appear that the disc type wheel possesses considerable advantages over wheels of wire-spoke construction. Disc wheels provide a large internal space in which the brake drums

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\*Proc. Inst. Aut. Eng., Vol. XVI, part 11, p.369.

can be accommodated, and there is no doubt that advantage will ultimately be taken of this space, for housing the landing gear springing.

It is usual practice to enclose spoke wheels with canvas or aluminum fairings, but these cannot provide such good protection for the brake apparatus as is possible with the disc type of wheel, where the disc sides form their own fairings.

The practice of attaching brake drums to the spokes of wire wheels does not appear to be entirely satisfactory, because it is difficult to imagine that adequate rigidity can be secured in this manner.

The only aircraft wheels, complete with brakes, that have so far been manufactured in quantities, are the Bendix and Sauzedde wheels. From the published weights, it appears that the disc wheel has still a further recommendation, for it is appreciably lighter than the wire type wheel. A table of these wheel weights is appended.

Tire size	Weight wheels (less tires) with brakes		Weight of brake only	
	Disc wheel Bendix type	Spoke wheel Sauzedde type	Bendix	Sauzedde
30 x 5	lb. 22	lb. 23.4	lb. 9.0	lb. 9.5
32 x 6	30	34.7	12.0	12.0
36 x 8	31	41.6	11.0	12.5
44 x 10	60	97.5	24.0	21.5

If the frontal area and aerodynamic resistance are not increased by the addition of brakes, then the total loss in performance will be due to the added weights of the brakes and operating gear.

### C o n t r o l

Brake control is usually carried out by connecting cables from the wheels to tilting type rudder pedals. This system makes it possible to apply the brakes either simultaneously or separately, while rudder control can be maintained at the same time.

In the case of landing gears fitted with a shock-absorbing leg of varying length, it is necessary to carry the operating cable down the fixed strut or radius rod, in order that brake action can be controlled without interference from the shock-absorbing member.

Various operating systems have been proposed using hand, foot and tail skid control. This latter method suffers from the inability to provide independent braking on each wheel.

In the case of hand- or foot-operated control, the effort of braking comes through the pilot's muscles, and the maximum effort is therefore limited. It is not considered possible to obtain a greater effort than 70 lb. through the hand or 45 lb. through the foot, and it is not usually possible to obtain a greater velocity ratio (between foot movement and travel of brake shoes) than about 50-1.

In view of the strictly limited effort available, it appears that it must be augmented on airplanes above 3000-4000 lb. gross weight. This external help will come from some form of servo mechanism, but it is not necessary to elaborate on any of these various systems at the present time. There are many possible combinations of control, and these present a wide scope for the exercise of ingenuity.

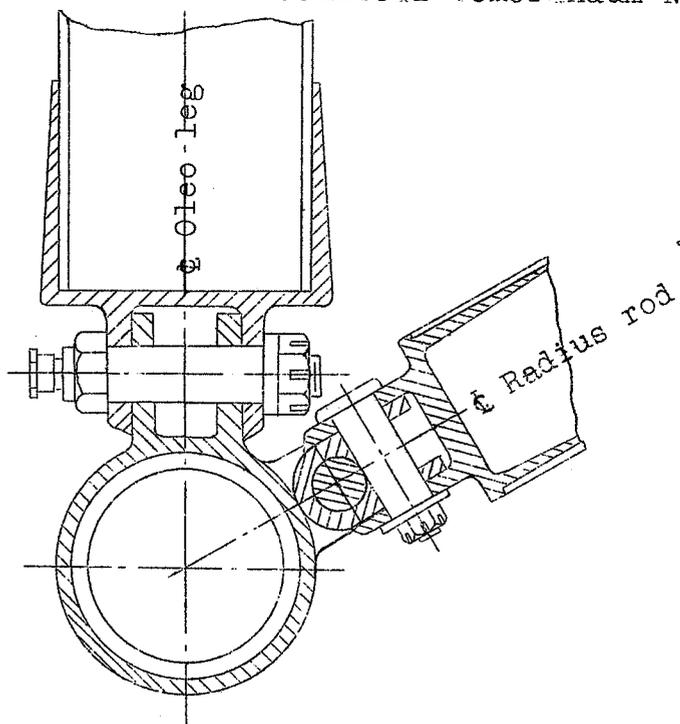


Fig. 1

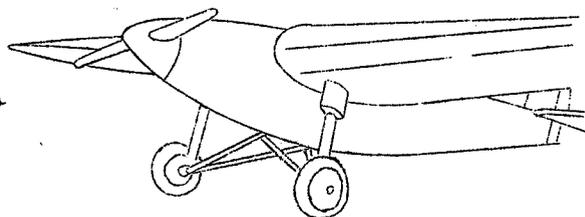


Fig. 2

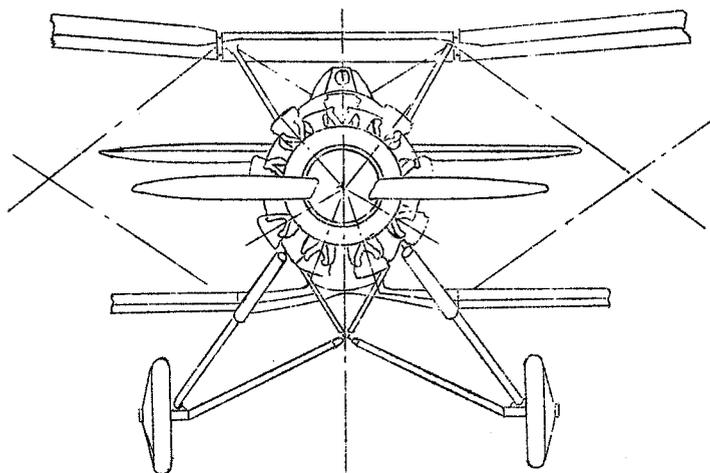
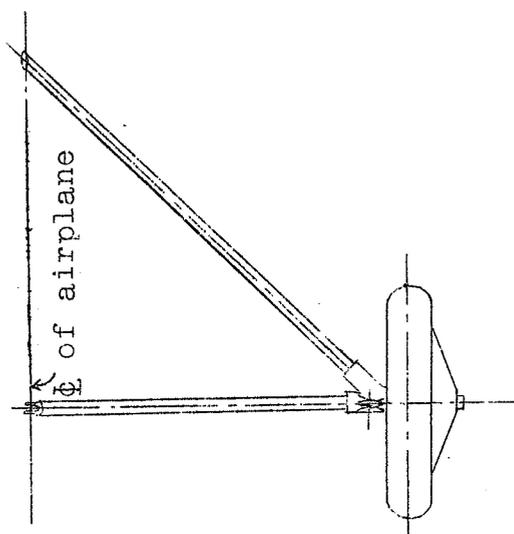


Fig. 3



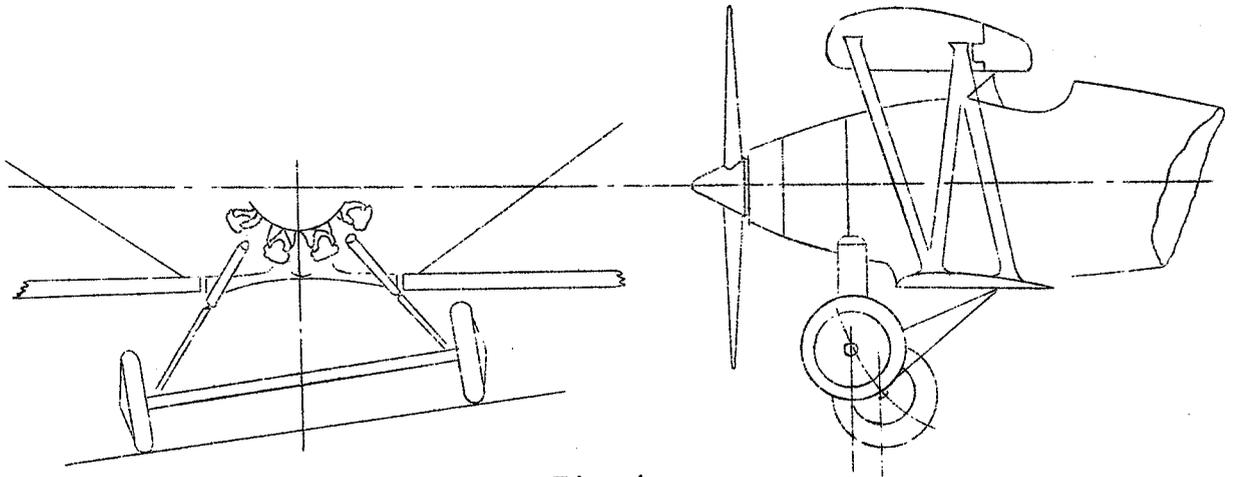


Fig. 4

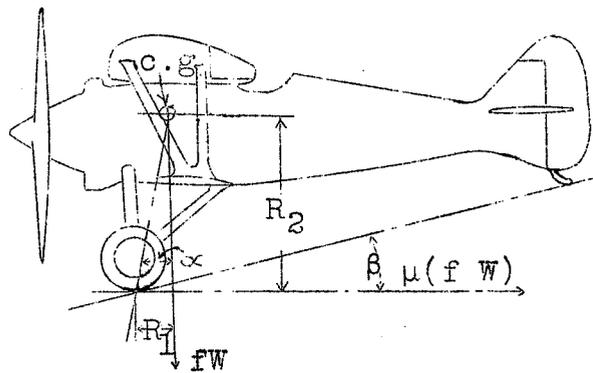


Fig. 5

Distributed load on wheels & tail skid vs velocity.  
Condition of landing: Tail down.

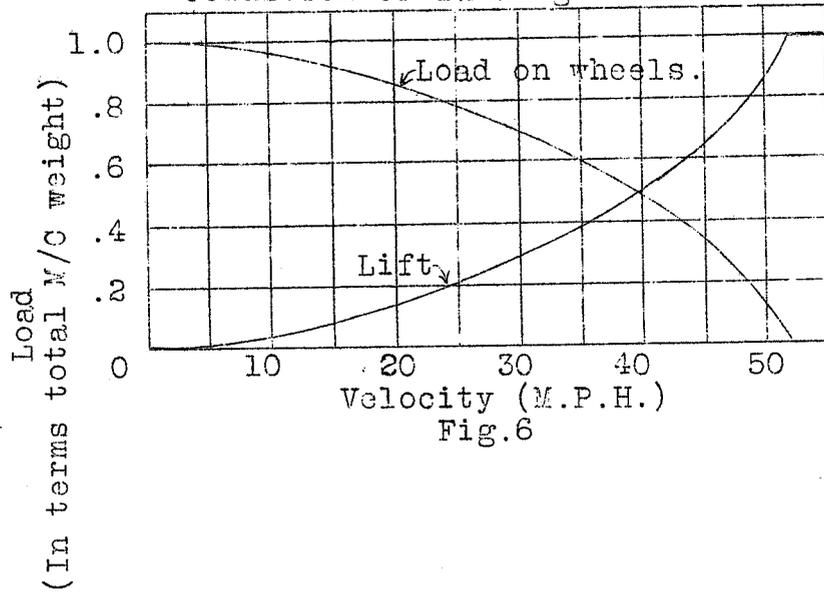


Fig.6

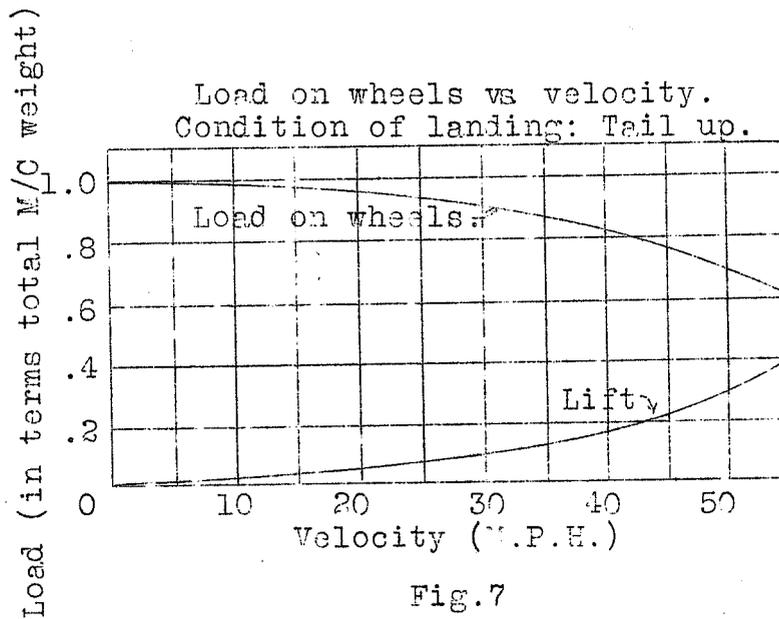
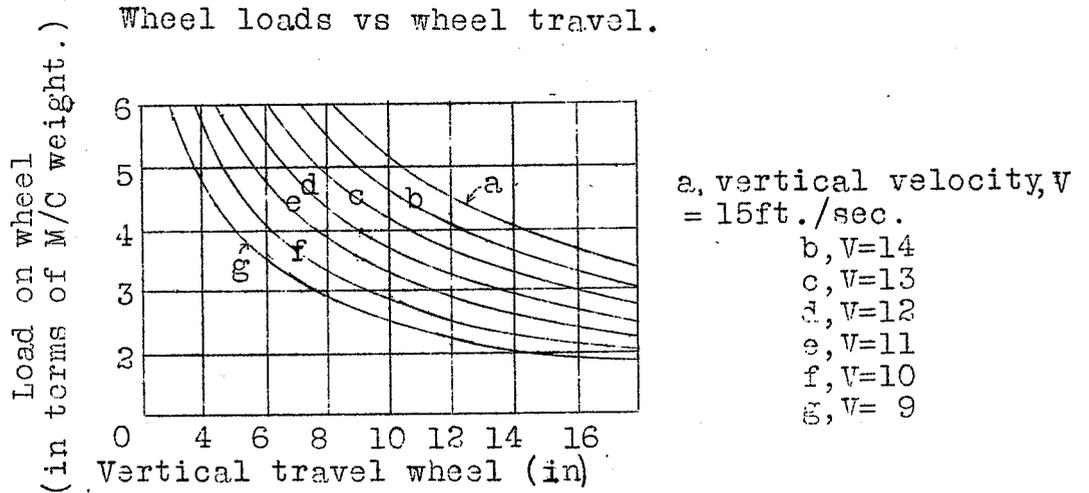


Fig.7



Assumptions (1) Airplane falling freely (not air borne)  
 (2) Uniform resistance throughout travel.

Fig.8

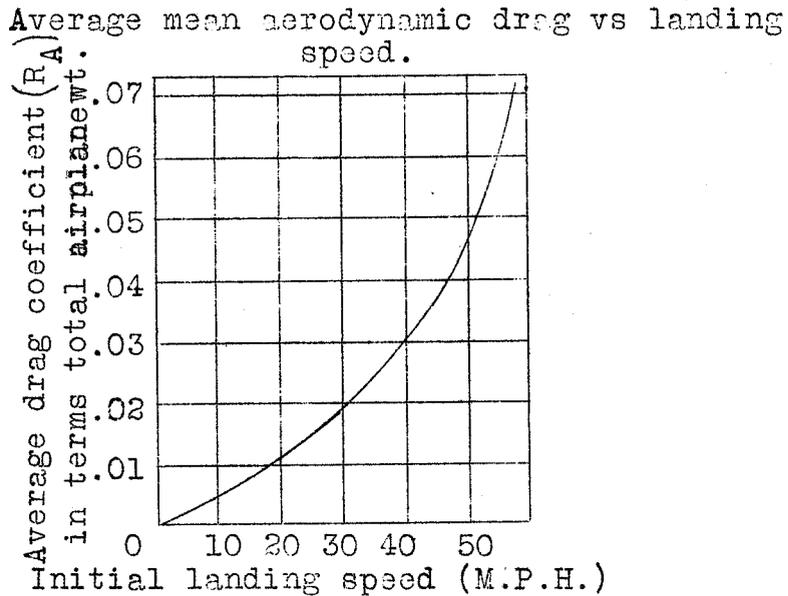


Fig.9

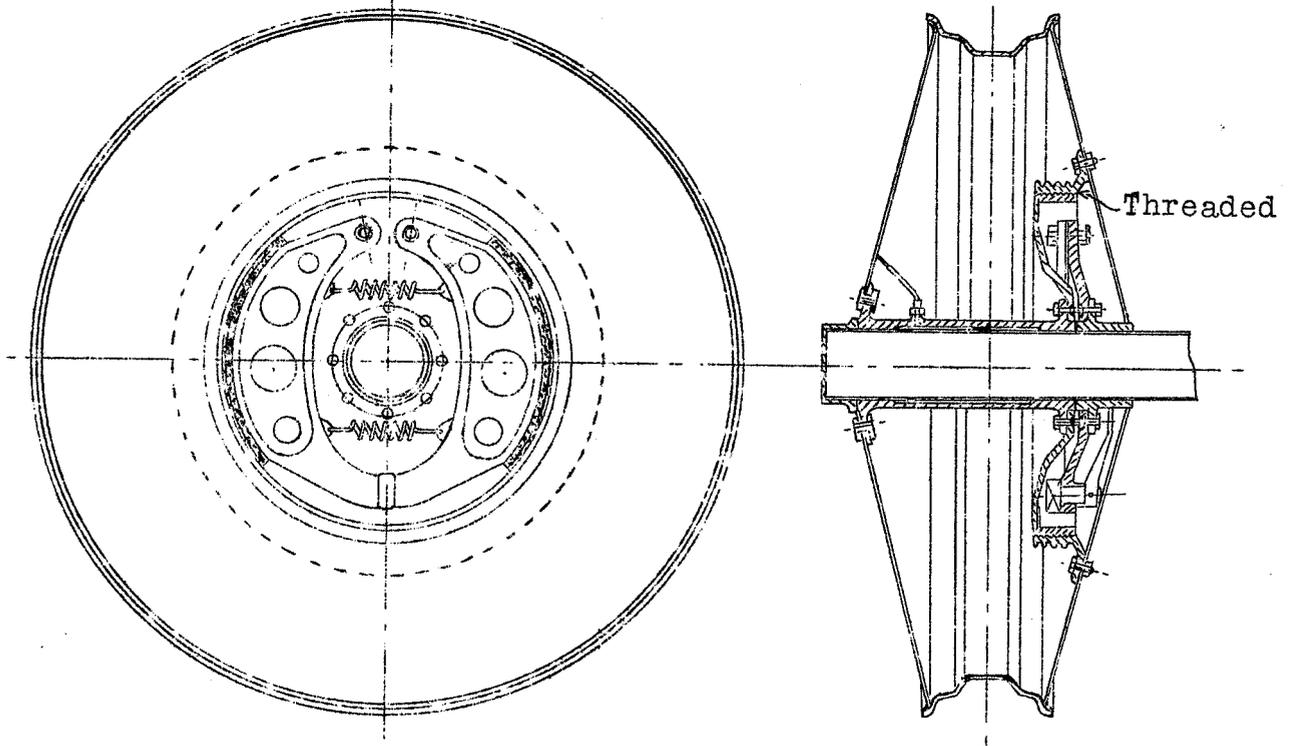


Fig.10

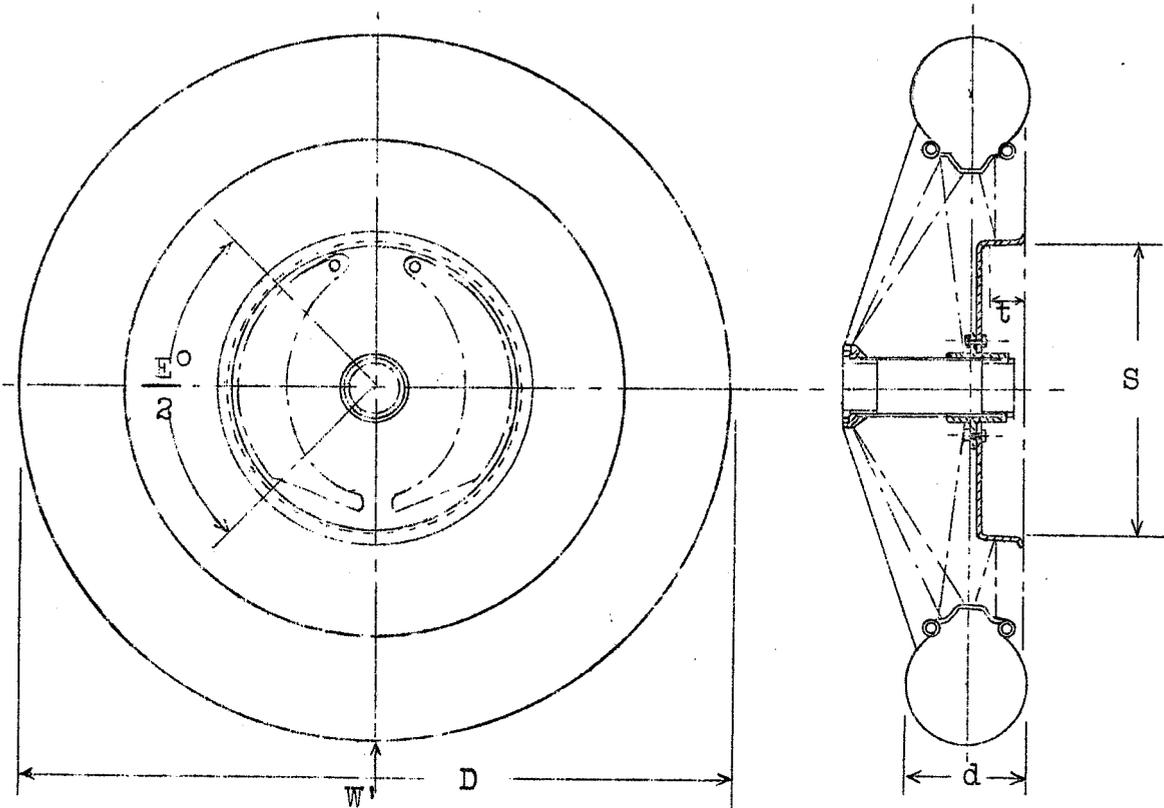


Fig.11

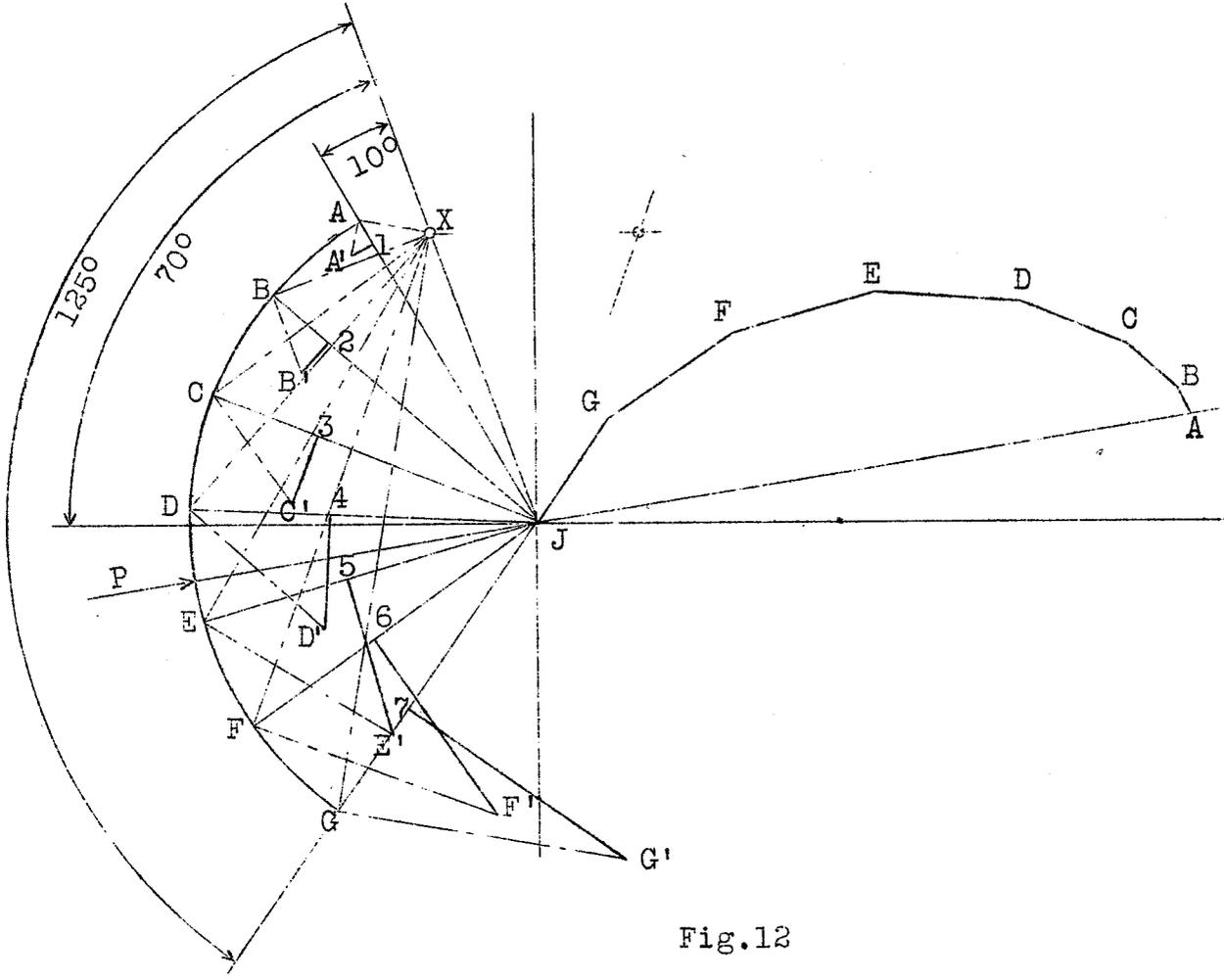


Fig. 12

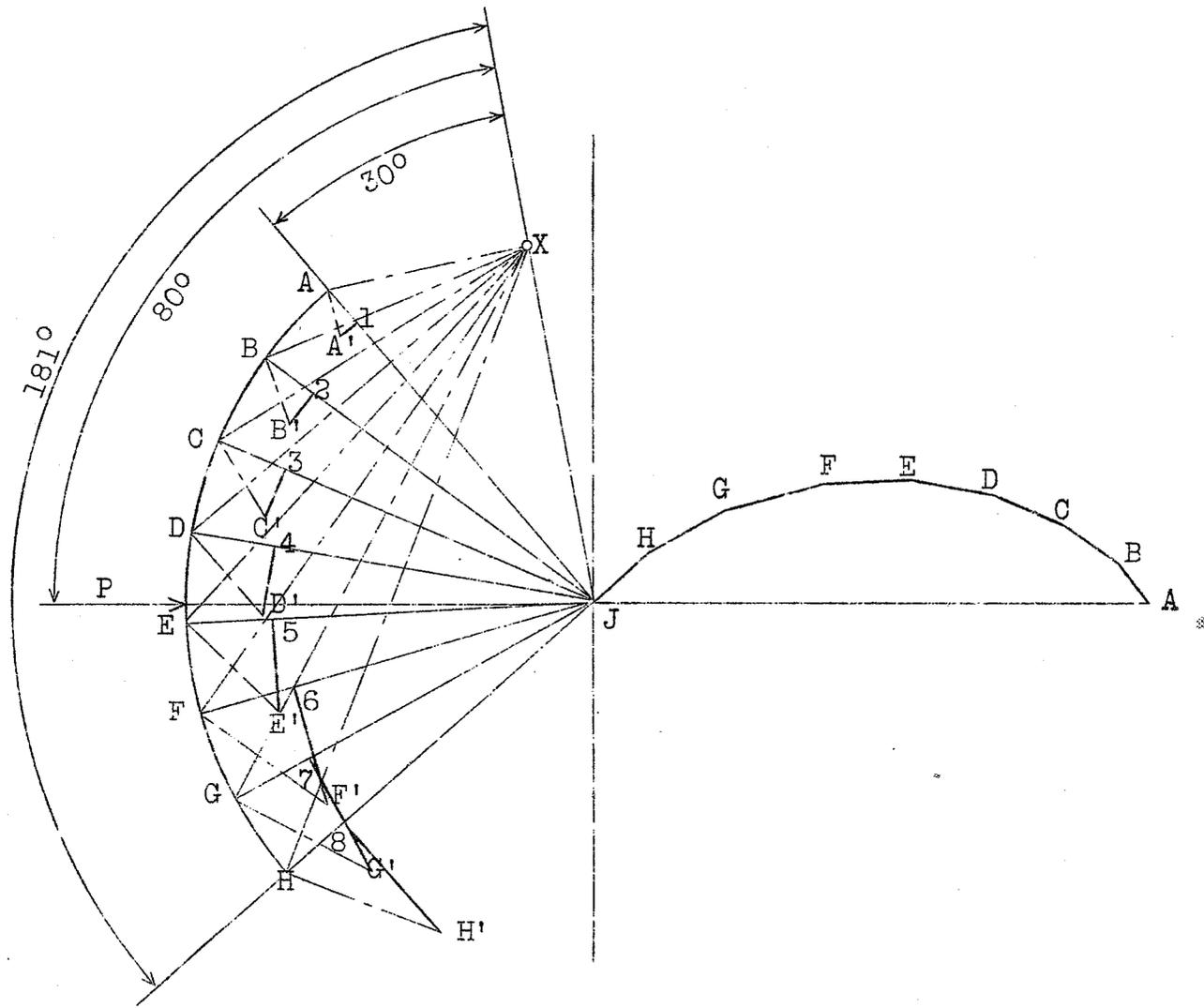


Fig. 13

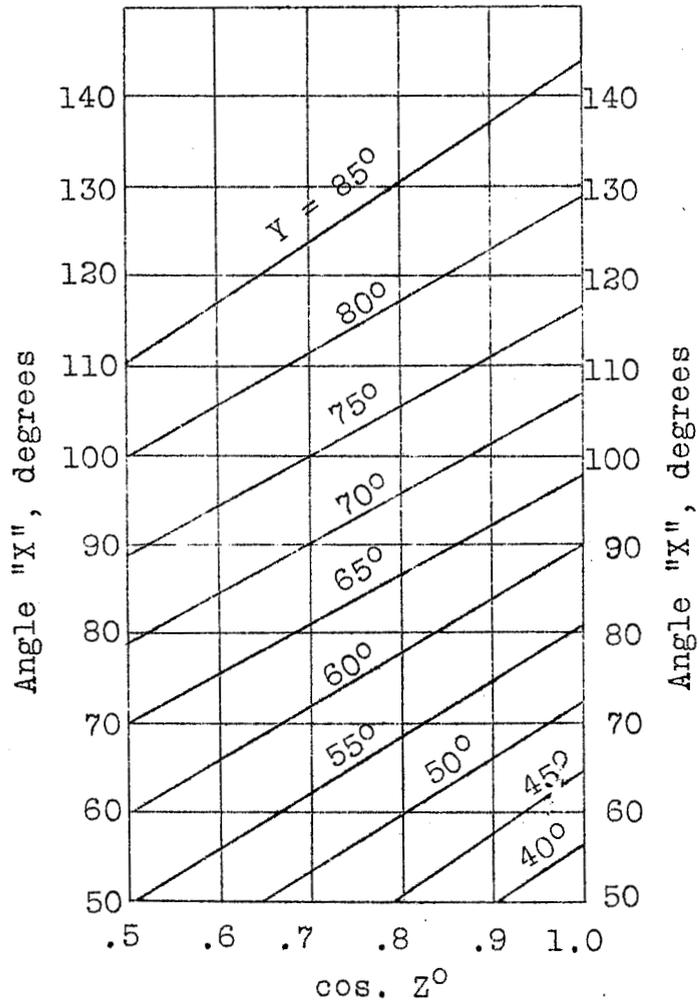
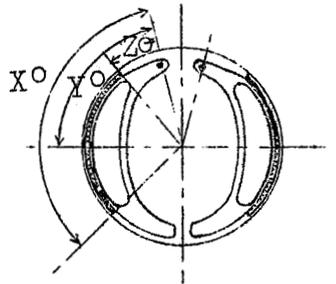


Fig. 14 Internal expanding shoe brake. Angular proportions.